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Translation

ELECTROMAGNETIC SHIELDING DESIGN FOR RADIO-ELECTRONIC EQUIPMENT

by

N. B. Polonskiy

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ELECTROMAGNETIC SHIELDING DESIGN FOR RADIO-ELECTRONIC EQUIPMENT

Moscow KONSTRUIROVANIYE ELEKTROMAGNITNYKH EKRANOV DLYA REA in Russian 1979 signed to press 19 Dec 78 pp 1-216

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[Text] A discussion is presented of the methods and physical principles of the electromagnetic shielding of radio-electronic equipment with filtration of the circuits introduced into the shielding.

The book is intended for a broad class of specialists in electronics and radioengineering working with electromagnetic shielding, the problems of the electromagnetic compatibility of radio-electronic devices, and radiation shielding. It can be used as a textbook.

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FOREWORD

Electromagnetic shielding is widely and variously used in many branches of science and engineering. In some cases, the shielding in the form of measures which encompass enclosure of the radio-electronic equipment itself and filtration of the networks and communication lines which go beyond the shields is the only means of localizing and attenuating the electromagnetic fields and radiation which inhibit stable, effective operation of the equipment. However, more frequently shielding is used along with other means of spatial, frequency, amplitude and polarization filtration of signals and interference, and in this case it takes on the nature of an auxiliary technical measure, the significance of which still almost always turns out to be highly significant for achievement of the necessary quality of the radiotechnical means and structures.

In spite of significant achievements, the general theory of electromagnetic shielding is still highly complex. The majority of its applications are limited to the scope of idealized conditions as a result of which the quantitative relations which would be suitable for designing actual shielding cannot be obtained.

Therefore, up to the present time many engineering problems have been solved and are being solved primarily by quantitative analysis and experimental development. Almost all of the visible results of the work on shielding and the results used in practice have been obtained by such methods.

This has led to the fact that in the given field of engineering a number of essentially different methods, technical solutions, designs and developments are being used for identical or similar purposes, and not all of them are optimal with respect to efficiency, technological nature, required material expenditures or other characteristics. The use of various design approaches for the same shielding purposes with identical initial data often leads to contradictions in execution of the radioengineering devices and incompatibility of their operational and economic engineering indexes.

Consequently, the problem arises of the generalization and classification of modern achievements in electromagnetic shielding design, the analysis of positive experience in design practice, operation and maintenance and the prospects for the development of this equipment, the formulation of the

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necessary recommendations, familiarization of radio specialists and other interested readers with the most significant results which have not been widely published for a variety of reasons.

The given paper is an effort to promote the solution of this problem considering the significance and the content of widely recognized papers by a number of Soviet and foreign authors: I. I. Grodnev, K. Ya. Sergeychuk, D. N. Shapiro, G. Kaden, and so on.

The book is divided into three chapters.

Chapter 1 presents a brief characterization of radio interference and methods of suppressing it considered, as is often done in engineering practice, as methods of diminishing the transfer of interference from its source to the receiver.

Chapter 2 analyzes and describes the structural designs of the basic shielding devices for radio equipment. The recommendations for the application of these designs and the materials for them are formulated and substantiated here. A study is made of the problems of the filtration of electric circuits introduced into the shielding. Experimental data and the design calculation for actual shielding are presented.

In Chapter 3 a study is made of the peculiarities of designing shielding for various purposes. Some example designs are presented which will provide the necessary shielding efficiency.

In this chapter primary attention is given to the most complicated shielding problems which arise during the operation of radio engineering and electronic devices under the effect of powerful radiators.

In many such cases a significant part of the efforts with respect to the localization or attenuation of the fields produced by such devices can be carried over to the creation of shielding which is external with respect to the equipment and not integral to it. Shielded facilities and enclosures constitute such additional shielding, the application of which offers the possibility of obtaining more efficient and varied technical designs. Many of the design elements of this shielding can be standardized with the equipment itself.

Unfortunately, the limited size of this book has not allowed identically complete coverage of all of the problems that are touched on in it. The author has limited some problems to short discussions and references to known papers. With respect to other problems only theoretical general solutions are presented. The author considers that the area of application of a significant part of the design solutions investigated in this book can be expanded and specialized significantly depending on the specific operating and design conditions of the equipment.

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The purpose and plan for the book were approved by Doctor of Technical Sciences, Prof V. A. Potekhin and Doctor of Technical Sciences, Prof A. P. Rodimov.

A. P. Rodimov made a number of valuable suggestions to the author with respect to the content of the book.

Candidate of Technical Sciences, Docent A. N. Polonskiy, who examined the entire work, was of great assistance. He made extensive comments and suggestions with respect to the content of the book. In addition, A. N. Polonskiy participated in the development of the materials for Chapter 2 and §3.1.

V. V. Chekhovich kindly made some of the data on the shielding materials available to the author, and L. S. Turin made it possible to include in the book the results of the development of wide-band, interference-suppressing filters prepared for publication by him.

The author expresses sincere appreciation to all of the mentioned comrades. The author is also indebted to reviewers, candidate of technical sciences Yu. V. Polozk, engineers M. L. Volin and G. B. Solov'yev-Yavits, who performed a critical analysis of the manuscript and made a number of useful suggestions for improvement of it.

Obviously, this paper has some deficiencies; therefore the author will gratefully receive suggestions and comments by the readers, which should be sent to the Sovetskoye Radio Publishing House (Moscow, 101000, Glavpochtamt a/ya 693).

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CHAPTER 1. PHYSICAL PRINCIPLES OF ELECTROMAGNETIC SHIELDING

1.1. Radio Interference and Methods of Suppressing It

The reception of signals in communication lines and radio lines for various purposes is realized, as a rule, in the presence of interference. It is impossible at this time to mention an area of application of electronic and radio-electronic equipment where its use is not limited by interference, without the consideration of which the operation of the equipment would be of little value.

The studies of radio interference have made it possible to classify them by interference of natural and artificial origin. The former include atmospheric, space and operating interference, and the latter, industrial, radio interference, mutual and intentional interference. The radio interference caused by electrostatic charges occupies an intermediate position.

The study and the development of organizational, organizational-technical and technical methods of attenuating mutual and industrial radio interference enter into the so-called problem of electromagnetic compatibility of radio devices which is one of the leading problems in the development of modern radio-electronics. A large number of papers have been published on the problem of electromagnetic compatibility. Without going into an analysis of the problem itself or the papers written on this problem, let us reference one of them [1] which provides the most complete statement of the problems.

In this paper an analysis is presented of the content of the problem of electromagnetic compatibility. A detailed classification of interference is presented, and apparently, it is noted for the first time that electromagnetic shielding is one of the most important engineering methods of solving the problem.

Considering the groupings or complexes of radio-electronic devices, they are divided into concentrated and distributed.

The concentrated complexes or radio-electronic devices are placed in more limited space, usually within one or several jointly or closely arranged units. The control systems for the radio-electronic devices of the same

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concentrated complex, as a rule, are general, interacting or at least having the possibility of exchanging information about operation of their own means (or means controlled by them). Therefore, the operation of the radio-electronic devices of one and the same mobile or stationary concentrated complex with mutual interference as a result of comparison of the operating frequencies or overlap of the required frequency radiation receptionbands is in practice excluded. The basic form of mutual radio interference is interference caused both by side and extraband radiation of the radio-electronic devices and by side and extraband reception channels. Sometimes this interference is called mutual radio interference in the near zone. Its appearance is caused in many cases not only by the properties and characteristics of the equipment provided for by its functional design, but also spurious communications and inductions which, in turn, can be a consequence of the poor design of the radio-electronic equipment or radio complex as a whole and also a consequence of the restrictions excluding the application of improved designs. Let us note that every type of radio-electronic equipment (transmitter, receiver or other device) made up of elements or units can also be considered as a concentrated complex of radio-electronic means. It is obvious that even without analyzing the physical principles and the technical possibilities of electromagnetic shielding it is possible to conclude that it is the most important means of controlling mutual radio interference of radio-electronic devices in the concentrated complexes, a technical measure having the purpose of attenuating spurious communications and inductions, localizing side and extraband radiation of the radio-electronic reception channels.

The distributed complexes are more spread out. The radio-electronic devices of such complexes, if they belong to different installations or are not combined by a general organization and control system, basically create mutual interference when operating in the overloaded segments of the radio frequency band. The interference of the radio-electronic devices of distributed complexes sometimes is called mutual radio interference in the far zone. The propagation and effect of mutual radio interference in the far zone usually take place in regular directions provided for by the functional layout of the radio-electronic equipment. It is obvious that the control of this type of interference is mainly by methods developed within the framework of the theory of noise suppression.

The development of the electrification of the country, the application of electrotechnical and radio-technical equipment in the national economy, public health, the use of equipment with complex electronic control systems and also the presence of an enormous fleet of electrical household appliances are leading to a sharp increase in the level of radio interference of industrial origin, interfering with the normal operation of radio-electronic equipment.

Another source of industrial radio interference is made up of electric power supply systems and elements of them, control systems, the automation

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of the radio-electronic devices themselves or complexes of radio-electronic devices. In many cases, for example, the effect of this source is predominant at the receiving centers.

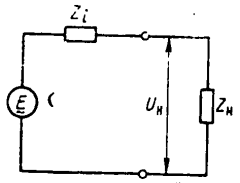

Figure 1.1. Simplest equivalent circuit diagram of an interference generator and receiver

Any electrical or radio devices, a complex or group of radio-electronic devices can be considered as a set of some number of noise generators and receivers connected in a defined way by coupling elements. It is obvious that this representation can be used for any spectral structure of the radio interference. It is natural that in the given case the application of the terms "generator" and "receiver" has a provisional nature. As for the communication elements, they can be real radio elements of a theoretical electric circuit and the structural elements of radio-electronic equipment or the space surrounding them reduced to an equivalent electric circuit. In the simplest case the circuit looks like the one shown in Fig 1.1, where Z_i is the complex internal resistance of the noise generator, and $Z_н$ is its complex load equivalent to the coupling element and the interference receiver, that is, a unit or element of radio-electronic equipment sensitive to this interference.

The entire structure of the couplings of the interference generators and their loads (the elements of radio-electronic equipment susceptible to interference) is sometimes called the equivalent noise-carrying network, independently of its complexity.

If the receiver is located at a distance of less than $\lambda/2\pi$, where λ is the wave length, then it is meaningless to talk about the fact that the interference reaches it by radiation or by interference-carrying conductors with a total resistance modulus of them equal to zero. It is more correct to consider that the interference reaches the receiver through its capacitive and inductive couplings to the interference source and the interference-carrying conductors or other interference-carrying elements of the radio-electronic circuitry and structural elements.

The equivalent electric circuits usually are obtained when analyzing the couplings of the source of interference to the receivers. These couplings (paths of interference propagation) can be symmetric and asymmetric (see Fig 1.2). The symmetric path (Fig 1.2, a) presupposes the propagation of the interference over two lines, and the asymmetric (Fig 1.2, b), over two lines and a common line (the "ground") with closure through the capacitances

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between the ground and both lines (Z_{H1}, Z_{H2}) and between ground and the housing of the source of interference (Z_H). The propagation of interference over a symmetric path usually turns out to be more favorable, for as a result of the reciprocal electromagnetic fields, significant interference condensation takes place, as a result of which its symmetric component will be less than the asymmetric component. Beginning with the fact that the asymmetric currents and voltages are predominant, it is considered that the intensity of the given interference generator can be characterized only by these components with sufficient accuracy for practice.

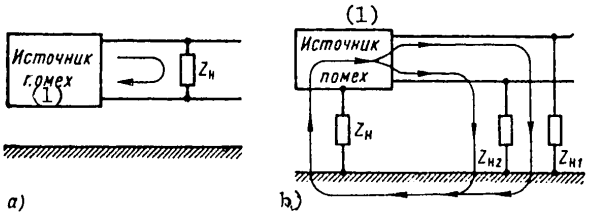

Figure 1.2. Symmetric and asymmetric couplings of the interference sourceand receiver

Key: 1. Interference source

In the simplest circuit on some frequency the load voltage will be

$$\dot{U}=\frac{\dot{E}}{Z_i+Z_н}Z_н, \qquad (1.1)$$

and the amplitude of this voltage will be

$$U_{mн}=\frac{E_m}{z_п}z_н, \qquad (1.2)$$

where E_m is the amplitude of the generator emf; z_H, z_{II} are the resistance moduli of the load and the total resistance of the circuit respectively [$Z_{II}=Z_i+Z_H$).

If the generation and transmission of the oscillations to load is the useful function of the circuit,then Z_i and Z_H are selected so as to obtain the maximum power of maximum voltage on Z_H.

However, the conditions of usefulness of the circuit must be satisfied only in a defined part of the spectrum. In the general case, along with generation of the useful oscillations, the generator creates a noise voltage also in the load [2]. In order to attenuate the interference to admissible levels, the matching additions with respect to power or with respect to voltage must be satisfied with the required accuracy only for the signal. This means that frequency-selective elements must be introduced into the system, the effect of which is equivalent to the operation of a shield or filters in the interference-carrying lines. Consequently, on the whole, the simplest coupling of the generator $\dot{E}$ to the load Z_H must satisfy the matching conditions only in the signal frequency band, and in the noise

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spectrum it is necessary to obtain $E_m/U_{mH}=z_П/z_H>>1$. Obviously, the stronger this inequality, the more effective the noise attenuation.

The solution of this problem is impossible without determining the frequency characteristics of the generator E, its internal impedance Z_i and load Z_H.

The spectral characteristics of the generator can be obtained by calculation or more reliable means of direct measurement of them using the measuring interference receiver [3], professional receivers, selective volt meters, and other analogous measuring devices. The application of nonspecialized equipment, for example, professional receivers, leads to complication of the measurement procedure and system, for it is also necessary to use standard signal generators, calibrated attenuators and coupling elements. In the simplest system when taking the spectral characteristics of the generator emf E, the condition $z_H>>z_i$ must be satisfied, which corresponds to approximation of the operating conditions of the circuit to the no-load conditions.

The most complicated is determination of the characteristics Z_i and Z_H which must be satisfied under operating or static conditions of the system. The measurements in the static state turn out to be inappropriate in a number of cases. This especially pertains to such sources of interference as rectifying and contact devices, the active elements of the receiving and transmitting radio channels, electronic instruments, mercury tubes, thyristors, and so on. For many situations, nevertheless, it is possible to limit ourselves to measurement of Z_i and Z_H under static conditions if the transition to the dynamic state does not lead to variation of the nature of these resistances (from capacitive to inductive and back) and variation of their moduli by more than 10-15%.

The equivalent circuit diagrams of sources and receivers of interference can be very complicated. Their analysis in general form and in specific applications in the presence of sufficiently wide band interference requires full application of the apparatus of electric circuit theory, which is not always possible in engineering practice requiring that operative estimates be obtained. In addition, many data on the equivalent circuit parameters are frequently unavailable, and exact determination of them, theoretical or experimental, entails significant expenditures of time and resources. The use of less precise data can lead to a situation where the strict solution will be out of the question, for the absence of the results of this solution excludes the possibility of developing the requirements on the error in planning the parameters; therefore the complex circuits are expediently characterized by the so-called interference transfer coefficient [4, 5] defined as the ratio of the maximum effective value of the interference voltage at the output of the generator (considering its internal resistance) to the effective value of the interference voltage at the input (on the input terminals) of the receiver:

$$K_П=U_П/E_A. \qquad (1.3)$$

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The voltage E_a is the analog of the emf induced in the equivalent antenna of the interference receiver. Both effective values are determined in the same frequency band and in the common time interval of the interference effect. Thus, the circuit diagram of the effect on the receiver is represented by three elements (see Fig 1.3):

Electroradio devices -- the source of interference represented in the form of a high-frequency oscillator (1), the coupling elements of the interference source to the input of the receiver represented in the form of a quadripole (2) characterized by the attenuation coefficient of the radio interference voltage on transmission of it from the source terminal to the receiver input; the radio receiver (3) represented in the form of a two-terminal network which is acted upon by the source of the interference through the above-indicated circuit quadripole.

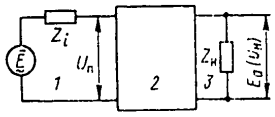

Figure 1.3. Circuit diagram of the effect of the source of interference on the receiver

The results of the analytical calculation of the interference transfer coefficient even in the simplest cases differ significantly from the true values; therefore it is determined experimentally.

In order to measure the transfer coefficient, an oscillator which has a sufficient output voltage level in the given frequency band is included in the interference-carrying network in place of the noise source. The voltage of this oscillator is measured at the points where it is connected to the interference-carrying network, and it is the voltage of the equivalent noise generator $U_П$. The voltage at the input of the receiver E_a arising under the effect of the oscillator is determined directly by a noise meter. Measures must be provided for here to match the resistances of the antenna-feeder system and the meter. In order to obtain the frequency function, the transfer coefficient is measured on frequencies or in frequency bands within the limits of the required frequency range.

In a specific device, the noise transfer coefficient to the individual nodes of a device can be determined analogously -- by connection of an outside standard signal generator to the noise source in the nonoperating state and measurement of the interference levels induced in each of the sensitive elements of interest to the designer.

In the simplest equivalent circuit diagram, if we adhere strictly to the definition of the transfer coefficient, it is equal to one. This is obvious, for it is assumed in it that the interference-carrying connections have resistances of zero. The inclusion of at least one additional two-terminal

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network in these circuits (see Fig 1.4, a) offers the possibility of analyzing even the simplest circuit with the help of the transfer coefficient.

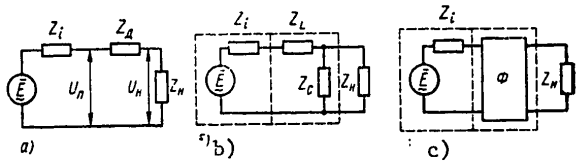

Figure 1.4. Interference suppression at the source itself

Actually, according to Fig 1.4, a, we have

$$K_{\text{п}}=U_{\text{п}}/U_{\text{п}}=z_{\text{дн}}/z_{\text{н}}, \qquad (1.4)$$

where $U_{\text{П}}$, U_{H} are the effective values of the interference at the generator output considering its internal resistance Z_{i} and the load voltage, respectively, and z_{DH} is the modulus of the total resistance of the series circuit made up of Z_{D} and Z_{H}, inasmuch as $z_{\text{DH}}\leqslant z_{\text{H}}+z_{\text{D}}$, then

$$K_{\text{п}}\leqslant(z_{\text{п}}+z_{\text{п}})/z_{\text{п}}=1+z_{\text{п}}/z_{\text{п}}. \qquad (1.5)$$

If we consider that in the interests of noise suppression it is necessary to achieve an increase in $K_{\text{П}}$, then a value determining the limits of the admissible values of the transfer coefficient is entered in the righthand side of the inequality.

From the presented formulas for $K_{\text{П}}$ of the simplest circuit with an additional two-terminal network it follows that:

As expected, the coefficient $K_{\text{П}}$ does not depend on the oscillator emf or, consequently, its spectral characteristics; this is true for all cases where the equivalent interference transfer circuit is linear;

The value of $K_{\text{П}}$ increases with an increase in z_{D} and a decrease in z_{H} in the required frequency range; this is equivalent, first of all, to the interference suppression measures at the point of their occurrence, secondly, in the propagation channel and, thirdly, an increase in the interference suppression of the receiver or mismatch of its input impedance to the noise generator.

Thus, depending on the specific conditions, the suppression of the radio interference can be realized at the source itself at the point of its occurrence, on the propagation paths and in the receiver. Technically, the use of the enumerated procedures simultaneously is the most efficient. In this case, one of them will be the basic method.

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The obvious possibility of improving the interference suppression in the device reduced to the simplest equivalent diagram consists in inclusion of elements between the oscillator and the load which can be represented by a quadripole with frequency characteristic similar to the characteristic of the L-type LC element. The inclusion of the capacitance C parallel to the load and the inductance L in the horizontal branch of the circuit (see Fig 1.4, b) permits $K_П$ to be increased as the interference frequency increases. If the inductive and capacitive resistances change places, it is possible to obtain the inverse dependence on the frequency. In the general case, if we include between the generator and the load a filter C (Fig 1.4, c) -- a low-frequency filter, high-frequency filter or band filter with given frequency characteristics in the transparency and suppression bands -- on consideration of the parameters of the resistances Z_i and Z_H we can obtain values of $K_П$ which satisfy the standards, the operating and technical conditions of the radio-electronic equipment. In real devices the circuit and structural elements of the radio-electronic devices, including the shielding, can play the role of the filters.

Increasing the interference transfer coefficient or the effectiveness of the interference suppression is always limited by the material expenditures and the characteristics of the radio-electronic equipment. Therefore the practical realization of the measures with respect to protection against interference is carried out to achieve some residual level of it insuring maintenance of the signal/interference ratio within the admissible limits. It is obvious that the minimum admissible value of the signal/interference ratio is determined beginning with the operating conditions of the radio-electronic equipment or the requirements on the equipment and the radio lines. The admissible signal/noise ratio must be established for the radio-electronic equipment as a whole and for individual devices of the equipment considering the entire set of interference.

The practice of suppresion and the statistical material on the radio interference levels created by various sourcs have made it possible to standardize the interference which is being improved continuously within the limits of increasing the effectiveness of using radio-electronic equipment.

On the basis of the standardization of the radio interference with known characteristics of its sources, requirements can be formulated on the suppression systems or the parameters of the interference-carrying network (the transfer coefficient). For example, if in accordance with the operating conditions of the radio-electronic equipment for given values of the signal voltage U_c, the interference voltage at the input of the investigated device $U_{П\ inp}$ must be such that $U_c/U_{П\ inp} \geq K_{c\ П}$,

then inasmuch as, according to the definition of the transfer coefficient in the given case $U_{П\ inp}=U_H=E_a$,

we obtain

$$K_п \geqslant (U_п/U_c)K_{сп}, \qquad (1.6)$$

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where, just as before, U_{Π} is the interference voltage at the input of the interference-carrying network.

Analogous estimates can be obtained for maximum and mean values of the interference levels for minimum and mean values of the signal level.

In the general case the mutual and industrial radio interference are random, containing, however, deterministic components. The levels of the deterministic components of the interference are determined in the broad sense by their type and the type of interference situation. In specific cases, the weight of the deterministic components turns out to be essentially dependent on the factors causing interference, the phenomena promoting the propagation of the interference and its penetration to the radio-electronic equipment, and the nature of the effect of the interference on the operating quality of the radio lines.

The most deterministic turns out to be the industrial radio interference of stationary installations and devices acting on the stationary radio-electronic equipment. Here the random component of the interference usually is negligibly small. In the majority of cases it appears possible and expedient to consider mutual radio interference in the near zone of stationary radio-electronic devices, their individual structures and elements, to be deterministic. As the mobility of the radio-electronic equipment increases and there is greater variety of the operating conditions of the radio devices, the random nature of the mutual radio interference in the near zone and the industrial radio interference becomes more and more perceptible. As for the mutual radio interference in the far zone, it is almost always purely random with the exception of such comparatively rare situations where the radio-electronic equipment making up the radio lines operates on strictly regulated frequency bands of the nonoverloaded segment of the radio frequency range in standard installations with invariant propagation conditions of the radio waves. It must be noted that the random nature of the mutual interference in the far zone has a significant effect on the mutual radio interference of the radio devices of concentrated units. The cause for this is the necessity of varying the operating conditions of radio devices as a result of the effect of the radio frequency situation in the far zone, that is, as a result of mutual interference of the radio-electronic equipment of the various radio lines placed on the various concentrated units.

The random nature of the radio interference does not exclude the necessity or the possibility of standardizing it. In the presence of a sufficient volume of statistical data, the standardization can be carried out most completely and reliably by the probability criteria with the required level of reliability.

In the absence of sufficiently complete statistical data on the radio interference, the operative evaluation of the required values of the transfer coefficient can be deterministic, performed on the basis of assignment of the most probable maximum and minimum signal interference levels. This

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operative estimate is, as a rule, high, excluding gross errors and determining the required effectiveness of the noise suppression system.

For example, for the first five television channels a signal field intensity of E_c=500 microvolts/m is required for $K_{c\ П} \geq 100$. If an industrial source of radio interference located in the reception zone creates smooth non-sinusoidal interference at the receiver input with an effective value of the voltage within the limits of the frequency band of the channel $U_П$=30 microvolts, then with an effective antenna height of h_D=0.5 meters we have $K_П \geq (U_П K_{c\ П})/(E_c h_D) = (30 \cdot 100)/(500 \times 0.5) = 12$.

Undoubtedly, this estimate and similar estimates are rough and high, as a result of which they are uneconomical. However, in the interests of solving the problems and, in particular, developing technical requirements for the shielding, these estimates can be suitable, especially under conditions which are close to deterministic.

The optimal requirements on the systems for suppression of mutual and industrial radio interference can be obtained only on the basis of analyzing the sufficient volume of statistical material.

The analysis of the statistical characteristics of the radio interference and also the methods of obtaining them is the focal point of a great deal of research and goes beyond the scope of this paper. As an example, it is possible to indicate references [6-9].

The suppression of the radio interference on the transfer paths is realized in the channel, which is a part of the interference-carrying network. By the interference-carrying channel we mean the set of elements and devices of the radio-electronic equipment and propagation means connecting one interference source (generator) to one receiver (an element of the equipment susceptible to this radio interference). In other words, the interference transfer channel is the part of the interference-carrying network which is isolated when investigating the elementary situation of the effect of one interference generator on one receiver. Here the other network elements (generators and receivers) not influencing the investigated generator and receiver, are excluded from the analysis, and in the presence of such an effect, it is taken into account in the equivalent channel parameters.

The interference transmission channel is distinguished from the radio communications channel by shorter extent, variety and complexity of structure, the presence of a large number of random elements promoting the propagation of the interference or suppressing it. The possibility of propagation of interference from the generator to the receiver along several paths gives rise to phenomena in the channel which are analogous to signal and noise fading in the radio communications channels. Thus, in general form the interference transfer channel can be simulated by a quadripole with variable parameters, the variations of which in time can be random. The channels with variable parameters are the subject of study of the theory

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and practice of communications and, above all, radiocommunications. However, the theory of radio communications cannot fully deal with the interference transfer channels as a result of the fact that they can be more complicated than radio channels. Therefore the comparatively few papers in which these channels are investigated cannot be considered sufficient for a complete, even approximate, solution of the problem of interference suppression. On the whole, it is found that the engineering solutions reached here are based primarily on the analysis of various special cases.

The analysis of the interference transfer channel for interference propagated by direct radiation of it, is the most complicated. In radio communications these problems pertain primarily to the study of the electromagnetic fields in the far radiation zone. In order to suppress mutual and industrial radio interference by various methods, including shielding of the interference sources or the elements of the radio-electronic equipment susceptible to them and individual radio devices, the investigation of the near zone fields is no less important than the far or intermediate zone. Here it must be emphasized that the radiators and the receiving antennas for mutual and industrial radio interference are in many cases not the antenna or antenna-feeder systems themselves, but all possible parts and structural assemblies of the radio-electronic equipment or mobile and stationary installations where this equipmentr is located, the cable and line structures, the electric power supply networks, control networks, signal and communication networks, and so on. In the far zone, the magnetic field is determined by the current, and the electric field, by the charges in the corresponding radiators. The field has a predominantly reactive nature, for the vectors E and H vary in time with respect to magnitude and direction analogously to the variations of the voltage and current in the reactive elements. In this zone for the oscillatory nature of movement of the main part of the energy, the electric and magnetic fields can exist separately at certain propagation points with predominance of one component or another, inasmuch as for distances of less than a wave length, for instantaneous values of the variable fields, the laws of constant fields are applicable.

The field in the near zone is essentially nonuniform, and the wave impedances of the field components are reciprocal. The electric field has high wave impedance, and the magnetic field, low. In [10] it is shown that if for normal incidence of a wave:

for the electric dipole $Z_E=\bar{E}_E/\bar{H}_E$,

for the magnetic field $Z_H=\bar{E}_H/\bar{H}_H$,

where $\bar{E}_E\bar{E}_H$, $\bar{H}_E\bar{H}_H$ are the complex amplitudes of the electric and magnetic components of the field respectively; Z_E is the total impedance of the medium of the electric component of the wave which for simplicity is called the electric wave impedance; Z_H is the magnetic wave impedance, then the

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values of the moduli of the indicated resistances for the near and far zones are determined from the expression

$$Z_E = \frac{Z_0}{1+(\beta r)^2}\sqrt{\frac{(\beta r)^4+1}{(\beta r)^2}};$$
$$Z_H = Z_0[1+(\beta r)^2]\sqrt{\frac{(\beta r)^2}{1+(\beta r)^4}}, \qquad (1.7)$$

where $\beta=2\pi/\lambda$.

Fig 1.5 shows the functions $Z_H=Z_H(2\pi r/\lambda)$ and $Z_E=Z_E(2\pi r/\lambda)$ corresponding to the formulas (1.7). In the limiting case for $\beta r<<1$, the most characteristic for the near zone is $Z_E\approx Z_0/\beta r$, $Z_H\approx Z_0\beta r$, $Z_E>>Z_H$.

In the other limiting case for $\beta r>>1$, the most characteristic for the far zone is $Z_E\approx Z_H\approx Z_0=377$ ohms. This is the case of formation of a wave in the far zone with identical values of the electric and magnetic components forming a single electromagnetic process. For the intermediate values of βr, Z_E and Z_H approach Z_0. For $\beta r\approx 0.71$ we have $Z_E\approx Z_H$, which corresponds to phenomena which are characteristic for the far zone. With a further increase in βr, we have $Z_H>Z_E$. However, with subsequent increase in βr this inequality attenuates and in practice for $r>3\lambda$ it is converted to an approximate equality, the accuracy of which increases monotonically with an increase in r. The passage of the curves through the point $Z_H=Z_E$ and attainment by them at $2\pi r/\lambda=1.15$ of extremal values equal to $Z_{E\ min}=0.68Z_0$ and $Z_{H\ max}=1.47Z_0$, indicate that beginning with $\beta r=0.71$, the magnetic dipole creates an electric field, and the electric dipole, a magnetic field. As is known, with an increase in distance the field energy created by an electric dipole damps inversely proportionally to r^3 for the electric component and r^2 for the magnetic component. In practice, for the electric component of the field, the attenuation must be considered proportional to $1/r^3$ for $r\leq 0.1\lambda$, proportional to $1/r^2$ for $0.1\lambda\leq r\leq 3\lambda$ and for $r>3\lambda$, proportional to $1/r$. The latter fact must frequently be considered, for the majority of the radio interference measurements both in the far and in the near zones are realized by determining the electric components.

The basic practical value of the functions $Z_H=Z_H(2\pi r/\lambda)$ and $Z_E=Z_E(2\pi r/\lambda)$ presented in Fig 1.5 consists in the possibility of determining the wave impedances of the field components at the given distance from the source and, consequently, approximate determination of one of the field components with the other known. The schematic for the calculation can appear as follows. For known λ, r, E or H, first βr is determined, then the corresponding values of Z_E/Z_0 and Z_H/Z_0 are found. Inasmuch as these values correspond to defined ratios of the field components, the latter are determined by elementary calculations. However, this solution is not unique from the point of view of determining the nature of the dipole.

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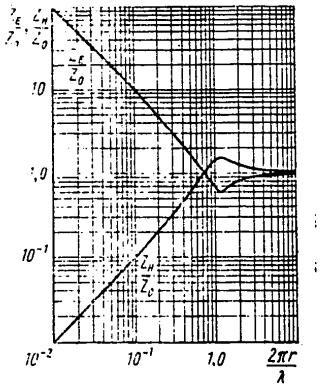

Figure 1.5. The wave impedances of field components as a function of $2\pi r/\lambda$

If the nature of the emitter is unknown, it is possible to give only a qualitative estimate, using the general properties of the interference source and considering that if the equivalent emitter is an electric dipole, then the value of the magnetic component of the field can be neglected.

It is possible to realize the quantitative estimate, comparing the fields of the equivalent horizontal frame with the field of the equivalent vertical electric dipole. Therefore when determining the electric component of the field intensity the measurements must be made both for horizontal and vertical positions of the meter antenna.

In the absence of possibilities of differentiated estimation of the field components with respect to nature, magnitude, and space, a more generalized characteristic of the emitter is used -- the effective height (area) of the equivalent antenna. Considering the phenomenon of decreasing the electric field intensity in the near zone on going away from the emitter, it is possible to consider that

$$E_{\text{п}} = \frac{\alpha h_{\text{д}}}{r^3} U_{\text{п}}, \qquad (1.8)$$

where α is the proportionality coefficient and the matching coefficient of the dimensions of the left and right sides of the expression; h_D is the effective height of the receiving antenna; r is the shortest distance from the antenna to the equivalent emitter; $U_П$ is the effective value of the interference voltage fed to the emitter.

In the far zone the electric and magnetic field intensities are proportional to the oscillation frequency, and the power of the oscillations is proportional to the square of the frequency, which explains the increase in

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efficiency of the antenna of fixed geometric dimensions with an increase in frequency.

The electric and magnetic fields in the propagated electromagnetic wave are continuously mutually transformed. At equal distances from the emitter the electric and magnetic fields are in phase and form a surface in the form of a sphere called the wave surface. Consequently, the electromagnetic waves propagated in space are spherical. With significant radius of the sphere, a small area on its surface can be approximately considered planar. Therefore in the emission zone with insignificant dimensions of the receiving antennas, we always operate with plane waves for which the ratios between the field components are known.

The space in which the interference is propagated on emission usually is not uniform. This can be made up of the parts of the structural elements of the radio-electronic equipment, the volumes inside and outside the equipment with different parameters of the internal environment, and finally it can be the territory of an industrial or radio engineering installation with the structures, communication lines, metal and other structural elements belonging to it. All of these elements change the propagation conditions of the radio waves, the configuration and distribution of the field. The determination of the resultant field intensity at any point of this space by analytical means is a highly complex problem even for stationary radio-electronic equipment and comparatively simple stationary installations, for on propagation of radio interference multiple reflection, interference and diffraction of the radio waves are observed. A solution of this problem for mobile radio-electronic devices and installations is still more complicated. Therefore the investigation of the electromagnetic situation of an area or section where interference is propagated is carried out experimentally with processing of multiple measurement results under various conditions by the methods of mathematical statistics. Here it is necessary to understand the basic laws of individual phenomena and the processes of formation and propagation of radio interference, which makes it possible to correct and use the experimentally recorded electromagnetic situation for interference suppression, adapting it to the specific conditions. It is possible to use various technical means for the indicated purposes.

In the general case in the presence of an obstacle on the propagation path with electrical parameters that differ from the wave parameters, the electric field varies as a result of the secondary field dispersed by the obstacle. The essence of these variations is analogous to the phenomena of reflection and refraction of waves at the interface of two media, but it is significantly more complicated here. The practical utilization of these phenomena to decrease the effect of the interference can also occur in the presence of natural barriers which must be taken into account in the specific situation.

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The attenuation of the interference propagated in the transfer channel by radiation can be obtained using the effects of radio wave polarization [11, 12]. The use of the polarization selectivity of the devices performing the functions of receiving antennas for the radio-electronic elements susceptible to the interference can decrease the effect of this interference significantly. Practice shows that in the absence of the possibility of broad application of branched polarization lattices it is possible to achieve some decrease in the effect of the interference source on the receiving antenna, orienting it perpendicularly to the radiator and thus obtaining the simplest polarization decoupling. In some problems of the design of radio-technical devices it appears expedient to use various materials and means of propagating the radio waves to obtain polarization decoupling of the sources and the receivers of the interference or in order to increase the polarization selectivity of the radio-electronic elements subject to the effect of the interference inasmuch as, as is known, a wave passing from one medium to the other in the general case is not only reflected and attenuated, but also changes its polarization. On the other hand, the natural barriers do not identically attenuate the waves of different polarization. Thus, for example, in the case of vertical radiation polarization the required attentuation is caused by the vertical barriers, just as for horizontal polarization, the horizontal barriers. The indicated phenomena almost always are considered when designing shields to the degree as is required by the electromagnetic situation, the structure of the object, the standard for suppressing radio interference and the type of shielding.

Two more important circumstances of the use of phenomena characteristic of the far zone must be noted in order to suppress the radio interference, realize the requirements with respect to joint and close arrangement of the radio-electronic elements and the radio-electronic devices and, consequently, the design of both comparatively small-scale shielding and large electromagnetic shielding systems.

The first fact is that the dependence of the radiation direction, diffraction, absorption, interference and polarization of the radio waves on the frequency does not have a sharply expressed nature. The frequency limits of these relations are "diffuse," and their comparatively wide-band nature does not offer the possibility of obtaining complete spatial and polarization separation of the interference sources and receivers as a result of shielding alone. Without taking special measures it is impossible to achieve a significant gain either with respect to the frequency compatibility of the radio-electronic means or the radio-electronic elements. Therefore when operating in the overloaded segments of the radio frequency band adjacent to or close to the frequency bands of radio-electronic devices and radio-electronic elements, the mutual separation of which at distances insuring the required damping of the interference is impossible, it is necessary to resort to time separation in the operation of the equipment and to the frequency filtration measures.

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The inclusion of the filters in the equipment can be highly varied. They can be in different channels, but they can also be elements of emitters and the receiving antennas essentially limiting their frequency bands. As an example it is possible to present the application of a lattice made of threshold waveguides installed in front of the receiving antenna and equivalent, as is known, to a high-frequency filter. Let us also note that the shielding of the device is in the near zone or the emitter directly itself is also wide-band. Therefore the application of the means of radio frequency filtration turns out to be no less necessary for decoupling of the jointly arranged elements inside the radio-electronic equipment and with joint placement of the radio-electronic devices than the shielding.

In the majority of cases, the shielding and filtration systems have a significant effect on the overall dimensional characteristics of the equipment, which forces in practice complete withdrawal from the realization of the required relations between the radio-electronic elements of the same installation by the emission of signals and resorting everywhere possible to the use of shielded feeders and cables.

The second circumstance consists in the fact that the far zone is characterized by the presence of the already-formed direction characteristics of the emitters and receiving antennas. In our investigation, each of these devices in the overwhelming majority of specific situations is not a specialized antenna-feeder system. It is possible to say that from the point of view of shielding the properties of the radiation and reception of electromagnetic waves are almost always side properties accompanying the basic functions of the radio-electronic elements. However, for any radio-electronic element that emits or receives radiation among the various types of transmitting or receiving antennas, an approximate analogy can be found to the configuration corresponding to this element, the geometric dimensions and the feed technique.

By the known radiation patterns of the analogous antenna, its operating conditions, the operating frequency range and other parameters it is possible approximately to determine the field structure for the given radio-electronic equipment and the possibility of the reception and emission of interference and also the nature of the interaction of this element with the other fields of the interference-carrying network. This means that the presence of the characteristics of the analog antenna and spectral characteristics of the possible emissions and reception channels permits to some degree estimation of the role of the investigated device in the general electromagnetic situation on the installations, prediction of it and the making of the corresponding preliminary decisions with respect to selection of the trends in the design of the system for suppression of mutual and industrial radio interference. It is obvious that the forecast can take into account not only the spatial and spectral characteristics of the emission and the reception channels, but also their energy indexes and the duration of the probable intervals of simultaneous operation of the radio-electronic devices.

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Usually the area of direct effect of the interference does not go beyond the limits of the circle, in the center of which the source is located, and the maximum radius is from 100 meters to several kilometers. In some cases, interference is detected at distances up to 10 or more kilometers from the installation containing the emitting devices. Frequently this occurs when the interference is propagated along some quite long line.

It is known that in the electromagnetic processes the concentration of electromagnetic energy takes place primarily not in the conductors, but in the space surrounding the conductor. As a rule, the conductor forms the boundary of this space in which electromagnetic processes take place. The higher the frequency and the higher the conductivity of the metal, the less electromagnetic energy penetrates into the body of the conductor. Therefore, the simplest two-conductor line, which is in the form of two linear parallel conductors close to each other, laid near the radiation source, independently of its purpose, turns out to be a carrier of this high-frequency energy.

Thus, even from a brief investigation of the types of radio interference under the methods of suppressing it, it is possible to conclude that along with the application of other technical means for this purpose it is possible to consider the complex utilization of electromagnetic shielding and filtration of the circuits to be basic.

The modern set of radio-electronic means is, as a rule, an organization of sufficiently high order. The determination of it as a system is entirely acceptable to it. Therefore it is more expedient to consider the electromagnetic shielding an attenuation measure primarily for intrasystem interference. The latter is not indisputable, for it is determined by the content which is included in the term of industrial-system and extrasystem interference.

The electromagnetic shielding is not only one of the methods of insuring electromagnetic compatibility of the radio-electronic devices, but it also permits the solution of the problems of biological shielding, an increase in the resolution of measuring equipment, improvement of the operating reliability of the radio-electronic equipment, the application of which is not connected with operation of the radio lines.

The properties of radio interference, the analysis of the possible methods of suppressing it and practical results achieved in this area permit us to consider electromagnetic shielding the most important and sometimes the only method of attenuating such interference. The application of electromagnetic shielding against industrial radio interference has a number of peculiarities, among which it is necessary above all to note the combination of electromagnetic shielding with filtration of the power supply networks, blocking, control and signalling, lending a complex nature to the electromagnetic shielding measures. The second most important characteristic is

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the increase in volumes of shielded spaces frequently to highly significant dimensions of the stationary industrial or scientific and technical installations.

The electromagnetic shielding is closely connected with radio engineering. This relation arises not only from the area of application and the goals of the electromagnetic shielding, but also the broad utilization of radio-technical methods for investigations of the shielding problems, planning and design and evaluation of the effectiveness of the shields. After the development of radio engineering, meeting its demands for the further assimilation of the radio frequency band, the creation of improved radios and providing for their operating conditions, electromagnetic shielding must expand its possibilities and overcome the limiting factors such as, for example, the dimensional characteristics of radio-electronic equipment, the complexity of its structural design, and so on. Electromagnetic shielding and radio engineering have to a great extent a common theoretical base on the theory of electromagnetic fields and the theory of electric circuits, and in engineering applications, on theoretical electrical engineering. With all that it has in common with radio engineering electromagnetic shielding still has a number of significant characteristics bending at perceptible independent value. The specific nature of electromagnetic shielding is primarily the great proportion of design activity calling on the experience and information from the fields of mechanics, physics, chemistry and material sciences. In the proper combination of design work with analysis of the causes of occurrence, paths of propagation and spectral characteristics of radio interference lies a significant part of the progress in shielding design.

1.2. Purpose and Basic Characteristics of Shielding

Electromagnetic shielding is designed for the localization in space of the fields created by the emitters of electromagnetic energy in order to attenuate or exclude the effect of the emitters on the sensitive elements of radio-electronic equipment and the equipment as a whole. Depending on the purpose, shields are distinguished with internal excitation of the electromagnetic field in which usually the interference source is placed, and the external electromagnetic field shields, inside which devices which are sensitive to these fields are placed. In the first case the shield is designed to localize the field in some space, and the second case, to protect against the effects of external interference.

The shielding, as a technical measure, is recognized as providing operating reliability for the radio-electronic equipment; it suppresses to the required level the effect of the unintentional radiation of electromagnetic energy preventing effective functioning of the radio-electronic elements. Determination of the purpose of the shield in each individual case is made considering the nature of the interference source and the element sensitive to it, their dimensions, spatial arrangement, type of communications

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lines and the admissible effect of the shield on the shielded elements.

As any area of engineering, electromagnetic shielding has some specific characteristics arising from its physical essence, the operating principle and specific conditions of application of the shields, which finds its expression in quantitative evaluation of the effectiveness of the shielding. In order to estimate the functional qualities of the shields, various characteristics can be used. The most generalized is the shielding efficiency.

By the shielding efficiency we mean the ratio of the effective values of the intensity of the electric field E_1 (the magnetic field H_1) at the given point in the absence of a shield to the intensity of the electric field E_2 (the magnetic field H_2) at the same point in the presence of a shield:

$$\vartheta_{0E}=\frac{E_1}{E_2}, \quad \vartheta_{0H}=\frac{H_1}{H_2}. \tag{1.9}$$

Here effectiveness is expressed in relative units (times). In practice usually the effectiveness of the shielding is represented in logarithmic units -- decibels:

$$\vartheta_E=20\lg\frac{E_1}{E_2}, \quad \vartheta_H=20\lg\frac{H_1}{H_2}. \tag{1.10}$$

It is obvious that the effectiveness of the shielding and the characteristics of the shields which are close to it formally and with respect to physical meaning are functions of space and frequency, and it is possible to consider the frequency band width in which the effective values of the field intensity are determined to be their parameters.

In some papers [13, 14], the effect of the shield is taken into account by the shielding coefficient

$$S=E_2/E_1, \tag{1.11}$$

which varies from 1 to 0, characterizing in the latter case the maximum shielding effect. In communications engineering the effectiveness of the shielding is expressed in nepers (Np):

$$B=\ln|1/S|=\ln(E_1/E_2). \tag{1.12}$$

Here for the conversion from one system of units to another the coefficient 8.7 can be used, then $E_{db}=8.7\ B_{Np}$.

When it is necessary to estimate the general effectiveness of the shielding beginning with the admissible value of the noise emf induced in the circuits

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of the radio-electronic equipment, the equivalent effective height of the device is used

$$h_0=U_H/E_1, \qquad (1.13)$$

where U_H is the effective value of the interference emf induced in the elements located inside the shield, meters; E_1 is the effective value of the external field intensity, volts/meter. The value of h_0 characterizes the effective height of the shield (by analogy with the effective height of the antenna).

Considering that the noise emf is proportional to the field intensity inside the shield, we find

$$h_0=aE_2/E_1=a/\vartheta_{0E}. \qquad (1.14)$$

A second characteristic of the shield quality is its effect on the parameters of the shielded element determined quantitatively by the reaction coefficient of the shield. For all types of shielding with the exception of static, as a result of the reflection of electromagnetic energy from the shield walls, interaction takes place between the shield and the shielded device. The shield, protecting the circuits, parts, and the oscillatory circuits from the effect of the external fields, has significant effect on the parameters of the shielded elements. As a result of redistribution of the electromagnetic field inside the shield, changes take place in their primary parameters, as a result of which, for example, the magnetic couplings change, the primary inductance of the coils decreases, the capacitance of the circuits increases, the active resistance increases, and then this leads to a change in the tuning frequency and Q-factor of the oscillatory circuits, energy losses, and so on. The relative changes in the parameters of the shielded elements can be taken into account using the coefficient

$$P_{ij}=1-A_{eij}/A_{0ij},$$

where A_{eij} is the value of the i-th parameter of the j-th shielded element in the presence of a shield; A_{0ij} is the value of the primary i-th parameter of the j-th element in the absence of a shield.

Each of the P_{ij} is a reaction coefficient of the shield to the i-th parameter of the j-th element.

Being given the admissible limits of variations of the parameters and knowing the dimensions of the shielded elements, it is possible to determine the dimensions of the shield, the material from which it must be made and the conditions of arranging the elements inside it.

1.3. Forms and Essence of Electromagnetic Shielding

In the general case the radio-electronic equipment is shielded by electromagnetic shields. However, frequently in the electromagnetic situation predominance of individual types of fields is observed; therefore in order

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to consider their specific nature, the following types of shielding are distinguished: electrostatic, magnetostatic and electromagnetic.

By electrostatic and magnetostatic shielding we mean the shielding of the fields of any frequencies of the induction zone. However, as will be obvious below, on high frequencies simultaneously with the magnetic field shielding there is electric field shielding which determines the unique process of electromagnetic shielding. It appears expedient to consider the essence of shielding as applied to low and high frequencies separately.

Electrostatic Shielding. If a conductor is introduced into an electrostatic field, then as a result of polarization, the electrons in it begin to move in the direction of the positively charged plate, and in the part of the conductor turned toward this plate, a negative potential arises. The opposite part of the surface of the conductor turns out to be charged positively. The positive and negative parts of the conductor create their own secondary field which is equal to the external field and has a direction opposite to it. Consequently, the external field and the field created by the conductor compensate for each other at all points inside the body and on the surface of the conductor. This explains the charged distribution only on the surface of the conductor. There is no field inside the conductor. This is a simple description of an example of the phenomenon of the electrostatic induction. The phenomenon of electrostatic induction is used to realize electrostatic shielding. Indeed, inasmuch as everywhere inside a metal body the field is equal to zero, it is sufficient to place a device subject to the electrostatic field effects in the inside cavity of a metal body and thus exclude the effect of the shield on the device.

Let us now assume that a charge of +q is placed in the center of a spherical metal shell. The charges -q arise on the inside surface of the shell, and +q on the outside surface, and the shield thus turns out to be ineffective. However, if we now connect the metal shield to ground (to the housing), the charges on the outside surface of the shell are drained off by the housing, for it has a very high capacitance, and the field turns out to be zero outside the shell. Thus, electrostatic shielding in essence leads to closure of the electrostatic field to the surface of a metal shield and removal of the electric charge to ground (to the housing of the instrument or device).

The grounding of an electrostatic shield, as is obvious, is a necessary element following from the essence of electrostatic shielding. Without grounding, the electrostatic charge almost completely loses its effectiveness. Attention is attracted to the fact that in the presence of charges both on the inside and outside surfaces of the shield, the field inside the shield is determined only by the internal charges and does not depend on the external charges at all. However, the inverse statement would be incorrect, for the charges located inside the shield create a field also outside the shield. Physically, this phenomenon arises from the appearance of induced charges on the outside surface, the effect of which can be neutralized by draining them to ground. Consequently, by grounding an

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electrostatic shield it is possible to achieve mutual shielding of both the inside space of the shield from an external field and the outside space from an internal field.

If the metal shielding fully compensates for the effect of the electrostatic field, then by using dielectric shield it is possible to attenuate a field of ε_r times, where ε_r is the relative dielectric constant of the material, for the field of the polarization-bound charges is subtracted from the free-charge field.

Let us place a dielectric in the field of two parallel metal plates. Under the effect of the electrostatic field forces the dielectric is polarized: the neutral molecules of the dielectric in electrical respects are converted to electric dipoles, and the dipoles already existing in the dielectric are rotated around the axes in the direction of effect of the field forces, forming electric charges on the lateral surfaces. On one side of the dielectric, a negative surface charge is formed, and on the other side, a positive charge. These bound electric charges of the dielectric create their own field in it directed opposite to the external field, which leads to a decrease in the resultant electrostatic field in the dielectric. The greater the dielectric constant of the dielectric, the greater the magnitude of its bound electric charges and the weaker the results of electrostatic field in it. Consequently, a device subject to the effect of an electrostatic field is expediently placed in the dielectric itself, for example, in alcohol (ε_r=26), in transformer oil (ε_r=2.2) or in distilled water (ε_r=81), and when using solid dielectrics the latter must be placed tightly against the shielded device.

The electrostatic shields are made of materials with high conductivity although in many cases materials are used which have sufficient strength and high anticorrosion properties but less conductivity. Most frequently the shields are closed volumes, metal baffles connected to the housing (frame) of the instrument. The application of screen, perforated or other nonuniform materials does not provide complete electrostatic shielding, for in this case part of the lines of force of the field penetrate into the shielded space.

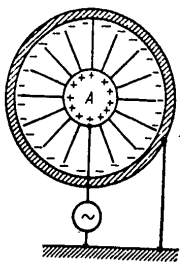

Figure 1.6. Electrostatic shielding principle

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If the source of the emf is variable (see Fig 1.6), then the charges in the body A will vary, and, consequently, the charges distributed on the inside surface of the shield will vary, which at each point in time will strive to have a polarity such as to compensate for the field of the body A. As a result of these variations, a variable current flows over the shield. The field compensation in the given case cannot be complete, for as a result of the appearance of a current in the walls of the shield, a voltage is incident on them. Therefore, the effectiveness of the shielding of the electrostatic field turns out to be dependent both on the thickness of the walls and on the conductivity of the shield material. With an increase in thickness and conductivity of the shield material, the residual field beyond the limits of the shield decreases, for the voltage drop on its walls decreases and the shielding efficiency increases simultaneously.

As applied to the quasistatic shield in practice at certain distances between it and the source it is possible to neglect the delay in the field variations and use laws for constant fields. In particular, at distances of less than 10 cm the results of analyzing the constant fields are suitable also for frequencies of no more than 300 megahertz. The shielding of the electric field under these conditions is in essence a problem of eliminating the spurious capacity coupling.

In Fig 1.7, a, the effect of the element 1 on the element 2 as a result of the presence of mutual coupling capacitance C_{12} is illustrated. If the source E creates a voltage U_1 on the element 1, then the emf induced on the element 2 will be approximately $U_2=U_1C_{12}/C_2$, where C_2 is the capacitance of the element 2 with respect to ground, where $C_{12}<<C_2$.

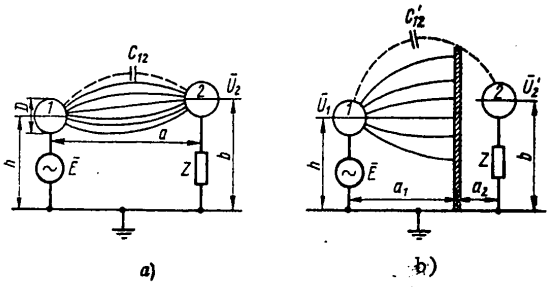

Figure 1.7. Schematic of the attenuation of a capacitive coupling

For cylindrical shape of the elements, the emf induced on element 2 is, according to [15], determined from the formula

$$\frac{U_2}{U_1}=2\frac{\pi hb}{a^2}\frac{1}{\ln(4h/D)}. \qquad (1.15)$$

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With the corresponding selection of the values entering into this relation (see Fig 1.7, a) it still remains significant. For greater attenuation of the coupling, a flat electrostatic shield is placed between the elements (Fig 1.7, b). This shield does not completely exclude the mutual coupling between the elements inasmuch as they remain weakly coupled as a result of the lines of force enveloping the shielded surface.

The shielding effectiveness of this type of shield can be approximately estimated by the formula

$$\vartheta_0 = U_2/U'_2 = C_{12}/C'_{12} \approx 5r_э^3/aa_1a_2, \qquad (1.16)$$

where r_e is the radius of the shield.

The shielding effectiveness in the given case is determined primarily by the possibilities of the penetration of the noise field behind the shield as a result of diffraction and scattering. These phenomena will be the most perceptible when $a_2 \sim a_1$. Therefore for commensurate a_1 and a_2, the shielding effectiveness turns out to be low, and for $a_1=a_2$, minimal. For an increase in the shielding effectiveness it is necessary to satisfy one of the conditions $a_2>a_1$ or $a_1>a_2$, the choice of which is determined by the purpose of the shield and the characteristics of the structural design of the shielded object or the source of interference.

As is obvious, the attenuation of the coupling between the elements depends on the natural damping as a result of separation of the elements (1.15) and damping introduced by the shield. Therefore it is expedient to characterize the total damping by the coupling coefficient

$$k_{\underset{(1)}{св}} = \frac{U_2}{U_1\vartheta_0} = 0{,}4\frac{hba_1a_2}{ar_э^3 \ln(4l/D)}. \qquad (1.17)$$

Key:
1. coupling

The smaller $k_{coupling}$, the smaller the mutual effect of the elements and the greater their decoupling.

Magnetostatic Shielding. The shielding effect of the magnetostatic shields is based on the closure of the magnetic field in the body of the shield as a result of its greater permeance by comparison with the surrounding space. This type of shield is identically suitable for shielding against the effects of an external magnetic field and for shielding the outside space against the effect of the magnetic field created by a force inside the shield. If, for example, we introduce a soft iron ring into a uniform magnetic field, it pulls the lines of force into itself, and the magnetic field inside the ring diminishes sharply (see Fig 1.8, b).

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The change in direction of the magnetic flux at the interface of two media with different permeabilities μ_{r1} and μ_{r2} is defined by the expression

$$\operatorname{tg}\alpha_1/\operatorname{tg}\alpha_2=\mu_{r2}/\mu_{r1}, \qquad (1.18)$$

where the angles α_1 and α_2 are illustrated in Fig 1.8, a.

If the permeability of one medium is infinitely large, that is, $\mu_{r2}/\mu_{r1}\to\infty$, then the angle α_1 approaches 90°. Thus, the flux leaves the surface with infinitely large permeability at a right angle. Although there are no media with infinite permeability, in practice it is considered that the magnetic lines of force are normal to the surface of ferromagnetic bodies.

Let us consider the magnetostatic shield (see Fig 1.9) in the form of a cube, the outside of which is equal to a. If the shield thickness is d, then the inside will be a-2d. In order that the boundary magnetic line of force not reach the inside part of the shield, it is necessary to satisfy the condition $\operatorname{tg}\alpha_2=d/(a-d)$. Then from (1.18), we find

$$d=\frac{(\mu_{r1}/\mu_{r2})\operatorname{tg}\alpha_1}{1+(\mu_{r1}/\mu_{r2})\operatorname{tg}\alpha_1}a, \quad 0<\alpha_1<\pi/2. \qquad (1.18')$$

From (1.18') it follows that the case is of greatest practical interest where $(\mu_{r1}/\mu_{r2})\operatorname{tg}\alpha_1<<1$, and, consequently,

$$d=(\mu_{r1}a/\mu_{r2})\operatorname{tg}\alpha_1 \text{ and } d\ll a.$$

For $(\mu_{r1}/\mu_{r2})\operatorname{tg}\alpha_1\sim 1$, d=a/2 is obtained which limits the dimensions of the inside cavity of the shield.

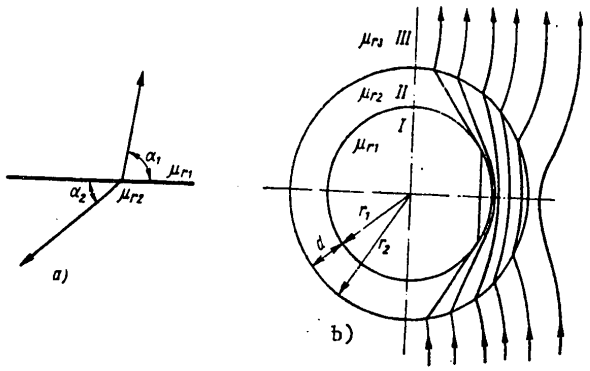

Figure 1.8. Magnetostatic shielding principle

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Thus, in order to insure significant attenuation of the magnetic field, the shield must be made of material with high relative permeability with great wall thickness. Here the greater the permeability of the shield material, the less the permissible thickness of its walls.

The shielding effectiveness of the cylindrical shield can be determined using Fig 1.8. In the regions I and III the relative permeability of the air $\mu_{r1}=\mu_{r3}=1$, and $\mu_{r2}>>1$. Then the shield effectiveness can be determined from the radio of the field intensities outside (region III) and inside (region I) the shield. In [16, 17] it is demonstrated that this ratio is

$$\Im^{(1)}_{0M}=\mu_{r2}\frac{r^2_2-r^2_1}{4r^2_2}. \qquad (1.19)$$

Key: 1. cylindrical

Expression (1.19 can be simplified somewhat. Since $r^2_2-r^2_1=r_2d(2-d/r_2)$, then

$$\Im^{(1)}_{0M}=0{,}25\mu_{r2}(d/r_2)[2-(d/r_2)]. \qquad (1.20)$$

Key: 1. cylindrical

When $d/r_2<<2$, it is possible to assume with sufficient accuracy that

$$\Im^{(1)}_{0M}=0{,}5\mu_{r2}(d/r_2). \qquad (1.21)$$

Key: 1. cylindrical

The shielding effectivness of a spherical magnetostatic shield with the same ratio r_2/r_1 is somewhat higher than cylindrical, and it is determined approximately from the expression

$$\Im^{(1)}_{0M}=0{,}7\mu_{r2}(d/r_2). \qquad (1.22)$$

Key: 1. spherical

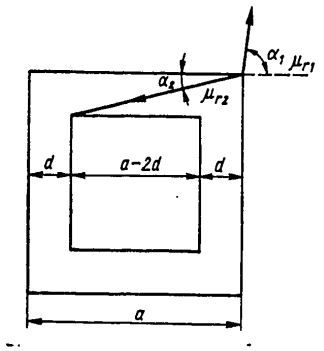

Figure 1.9. Magnetostatic shield

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The effectiveness of the rectangular shield can be calculated by formula (1.20) if it has the shape of a rectangular parallelepiped with a square base, the side of which is taken in (1.19) equal to the cylinder diameter. On the whole the effectiveness of the magnetostatic shields is low. For example, a shield made of special Armco alloy in which μ_r=3000, at a radius of 40 cm and a thickness of 1 cm, insures effectiveness of 37.5, which is only a total of 31.5 decibels. A shield of this thickness turns out to be very heavy and complicated to make.

In order to increase the shielding effectiveness in a number of cases multistage magnetostatic shields are used which are made up of several layers but thinner material. The required shielding effectiveness can be obtained for the two-layer or three-layer shield. The simplest of the multilayer shields -- the two-layer shield -- must be constructed so as to insure closure in the outer shell of the lines of force of the field which go beyond the walls of the first inside layer. For this purpose, both the wall thickness of the shells and the spacing between them must be properly selected. In practice the spacing between the shells is made greater than the thickness of the shell. In the first approximation the spacing between the shells is assumed equal to the spacing between the first shell and the nearest edge of the shielded object, and the thickness of each shell is taken no more than 1...1.5 mm.

Under these conditions, considering that the damping of the interaction between the shells in the presence of an air space is equal to zero, with sufficient accuracy for practice it is possible to set the shielding effectiveness of a multilayer shell equal to

$$\Im_{\text{эк}}=\left(0{,}5\mu_{r_2}\frac{d}{r_2}\right)^n, \qquad (1.23)$$

where n is the number of shells.

For the above-investigated example with Armco alloy, setting d=0.15 cm and n=2, we find that the shielding effectiveness will be 30 decibels.

When shielding constant magnetic fields, it is necessary to follow the following general recommendations:

Use materials with the highest possible initial permeability;

Avoid joints and seams with high reluctance on the path of the magnetic lines of force of the interference field in the structural design of the shield;

Do not allow fastening of the shielded element for the shells of the shield with steel parts which form paths with low reluctances for the magnetic lines of force of the interference;

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Increase the shield effectiveness without increasing the thickness of the material but by using several thin shields located at the greatest possible distance from each other.

Let us propose that an alternating current flows along the shielded turn instead of a direct current. The variable magnetic field of this turn, penetrating the shield, induces a variable emf in it, as a result of which alternating current flows through the shield. The shield behaves as a short-circuited turn placed in a variable magnetic field. The magnetic field of the eddy currents flowing through the shield is superposed in the outside space on the field of the shielded turn close to 180° out of phase, and attenuates it. The lower the resistance of the shield walls and the greater their thickness, the less the difference between the field intensity of the eddy currents flowing through the shield and the field intensity of the shielded current created outside the shield. Here the closer the phase difference between the fields to 180°, the greater their mutual compensation, the less the residual field outside the shield which means, the greater the shielding effectiveness.

With an increase in frequency, the phenomenon of nonuniform distribution of the eddy currents increases in the cross section of the shield material, that is, a surface effect is observed which is accompanied by concentration of these currents on the surface of the shield. A characteristic feature of the surface effect is the depth of penetration, by which we mean the distance along the direction of propagation of the wave at which the amplitude of the incident wave E (or H) decreases by e=2.7 times. The higher the frequency, the less the depth of penetration and the higher the shielding effectiveness. Thus, the depth of penetration also characterizes the shielding properties of the shield material.

Consequently, the shielding of the magnetic fields, just as electric fields, is made up of two processes: compensation of the field of the shielded turn by the eddy current field, just as in the short-circuited turn, and attenuation of the field on penetration of it through the shield walls. Until the thickness of the shield is less than the depth of penetration (for low frequencies), the field's compensation of the shielded turn by the shield field (as a short-circuited turn) is decisive. With an increase in frequency, when the thickness of the shield walls becomes greater than the depth of penetration, the attenuation of this field on penetration of it into the body of these walls can be decisive.

What has been discussed above leads to the conclusion that with an increase in the dimensions of the magnetostatic shield and an increase in frequency, the damping introduced by it decreases, for the effect of these factors is equivalent to a decrease in the permeability. Indeed, with an increase in frequency, the role of the eddy currents in the shield increases, the depth of penetration decreases, and, consequently, its permeance decreases, which is a function of the dimensions and the permeability of the shield material. Under these conditions the magnetostatic shield will behave as

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a magnetic shield, for as a result of a sharp decrease in the equivalent wall thickness of the shield, the phenomenon of shunting of the magnetic flux of the interference field disappears.

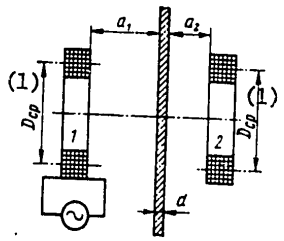

Figure 1.10. Attenuation of the inductive coupling by an unclosed flat shield

Key:
1. mean

In magnetic shielding practice flat unclosed shields are used. In the case of the effect of one magnetic circuit on another with close mutual arrangement of it, significant attenuation of the mutual inductive coupling can be obtained by placing a flat metal shield between them (see Fig 1.10). The effectiveness of the shield $\Theta_0=M/M_{12}$, where M is the mutual induction coefficient between the coils in the absence of a shield; M_{12} is the mutual induction coefficient between the coils in the presence of a shield.

In [18] it is recommended that the attenuation of the coupling between the coils be characterized by the coefficient:

For a copper shield

$$\underset{(2)}{K_{oc}}=10\lg[(6{,}35\underset{(3)}{D_{cp}}df)^2+1]\ \underset{(1)}{\text{дБ}}, \qquad (1.24)$$

Key: 1. decibels; 2. coupling attenuation; 3. mean

For an aluminum shield

$$K_{oc}=10\lg[(4D_{cp}df)^2+1]\ \text{дБ}, \qquad (1.25)$$

where D_{mean} is the mean coil diameter, cm; d is the shield thickness, cm; f is the frequency, kilohertz.

Formulas (1.24, 1.25) provide satisfactory accuracy under the condition that the width of the shield (perpendicular to the plane of the figure) exceeds D_{mean} or a_1+a_2, depending on which of these values is greater.

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1.4. Electromagnetic Shielding

Shielding using eddy currents insures simultaneous attenuation of both magnetic and electric fields. This provides the basis for calling this shielding procedure electromagnetic. The shielding effectiveness of such a shield in the near zone (the induction zone) will be different for the field components. Therefore, as a rule, for the near zone it is necessary to calculate the shielding effectiveness of each of the field components individually, assuming in this case that in the far zone (radiation zone) the shielding effectiveness of the components will be identical.

The physical essence of electromagnetic shielding, considered from the point of view of the theory of an electromagnetic field and the theory of electric circuits, reduces to the fact that under the effect of a source of electromagnetic energy on the side of the shield turned toward the source, charges occur, and in its walls, currents, the fields of which in the outside space are close with respect to intensity to the field of the source, and with respect to direction they are opposite to it, and therefore mutual compensation of the fields takes place. This investigation is simplified inasmuch as the nature of the electromagnetic shielding is more complex.

From the point of view of the wave representations, the shielding effect is manifested as a result of multiple reflection of the electromagnetic waves from the surface of the shield and attenuation of the wave energy in its metal body. The reflection of the electromagnetic energy is caused by noncorrespondence of the wave characteristics of the dielectric, within the limits of which the shield is located, and the shield material. The greater this noncorrespondence, the more the wave impedances of the shield in the dielectric differ, the more intense the partial shielding effect determined by the reflection of the electromagnetic waves.

The effectiveness of the closed electrically sealed[1] shield is defined by the formula

$$\mathcal{Э}_0 = \underset{(1)}{\mathcal{Э}_{отр}} \underset{(2)}{\mathcal{Э}_{погл}} \underset{(3)}{\mathcal{Э}_{вн\ отр}}, \qquad (1.26)$$

Key: 1. refl; 2. absorbed; 3. internal reflection

where $\mathcal{Э}_{отр}$ is the attenuation of the energy of the incident wave as a result of reflection at the interface; $\mathcal{Э}_{погл}$ is the attenuation as a

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[1] By the electric (magnetic) seal of a shield we mean its capacity to limit the penetration of the lines of force of the electric (magnetic) field outside or inside the shielded space. Correspondingly, the absence of any penetration means complete seal.

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result of damping of the wave energy in the body of the shield; $Э_{вн\ отр}$ is the attenuation as a result of internal reflection in the shield itself.

Usually for $Э_{погл} \geqslant 10$ decibels, we set $Э_{вн\ отр} \approx 1$. Therefore, we shall consider only two components of the shielding effectiveness

$$Э_0 = Э_{отр} Э_{погл} \qquad (1.27)$$

or in decibels

$$Э = 20 \lg Э_{отр} + 20 \lg Э_{погл}.$$

Let us begin with the investigation of an infinite flat shield on which a plane wave is incident. Under these conditions the magnitudes of the losses to reflection and absorption are determined identically, for in the body of the shield material both the incident and reflected layers are considered as plane waves. Let us find the value of the component of the shielding effectiveness determining the effect of the absorption of the electromagnetic energy. In the metal the electromagnetic wave damps in accordance with an exponential law. The measure of the rate of this process is the depth of penetration of the wave or the thickness of the surface layer δ. On passage of the wave through the thickness of the surface layer δ it attenuates by e times. If the thickness is equal to d, it will attenuate by $e^{d/\delta}$ times. Then

(1)

$$Э_{погл}\ [дБ] = 8{,}7 (d/\delta). \qquad (1.28)$$

Key: 1. decibels

The depth of penetration is a constant which characterizes the shield material and depends on the frequency,

$$\delta\ [м] = 0{,}03 \sqrt{\frac{\lambda \rho}{\mu_r}} = 0{,}52 \sqrt{\frac{\rho}{\mu_r f}}, \qquad (1.29)$$

where ρ is the specific resistance of the shield material, ohm-m; λ is the wave length in the air, m; f is the frequency, megahertz; μ_r is the relative permeability of the sheild material.

The determination of the depth of penetration for ferromagnetic materials is complicated, for in them μ_r depends on the frequency. For varieties of steel used for shields, with an initial relative magnetic permeability $\mu_r \sim 180$ on a frequency of f=0,1 megahertz in the frequency band to 1000 megahertz, according to our data, the magnetic permeability, depending on the frequency, can be estimated by the formula $\mu_r \approx 150-30f$, where f is the frequency, megahertz.

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The shielding effectiveness as a result of absorption alone, in accordance with (1.28) and (1.29) will be

$$Э_{погл}\ [дБ] = 290d\sqrt{\frac{\mu_r}{\lambda\rho}} = 16{,}7d\sqrt{\frac{\mu_r f}{\rho}}, \quad (1.30)$$

where d is the thickness of the shield material, meters.

As is obvious from (1.30), the wave damping as a result of absorption increases with an increase in frequency. It depends only on the parameters of the medium in which the wave is absorbed, and it does not depend on the field components.

Considering the operation of the shield as the process of interaction of the phenomena of reflection and absorption of an electromagnetic wave and considering that in the general case the attenuation coefficient

$$K = \exp\left(-\frac{\sqrt{2}d}{\delta}\right), \quad (1.31)$$

we find the shielding effectiveness of the flat shield of infinitely large dimensions when a plane wave is incident on it:

$$Э_{0\,пд} = |(Z_д + Z_м)|^2/4Kz_д z_м, \quad (1.32)$$

Key: 1. plane (1)

where Z_M, Z_D are the wave impedances of the metal and the medium; z_M, z_D are the moduli of the resistances Z_M, Z_D, respectively.

Formula (1.32) is a general expression of the effectiveness of a flat shield when a plane wave is incident on it considering the shield damping in the body of the shield and the reflection from its surfaces. The consideration of multiple reflections in the body of the shield leads to a decrease in the effectiveness by

$$\Delta = 1/(1 - K^2R^2_2)\ \text{times}, \quad (1.33)$$

where R_2 is the internal reflection coefficient.

It is possible not to consider the decrease in effectiveness when the thickness of the shield is greater than the depth of penetration into it of a field on a given frequency, but it cannot be neglected when the shield thickness is less than the depth of penetration. Therefore in electromagnetic shielding practice electrically thin and thick materials are distinguished. For electrically thin material $\delta > d$, and the calculation of the effectiveness is made considering the internal reflections.

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The effectiveness of the flat shield of infinitely large dimensions placed in the air and irradiated by a plane wave at $d/\delta<0,8$ considering internal reflections will be

$$\Э'_{0пл}=60\pi d/\rho, \qquad (1.34)$$

and the effectiveness of the same shield for $d/\delta>0,8$, that is, a shield of electrically thick material, is defined by the expression

$$\Э_{0пл}=65(\delta/\rho)e^{d/\delta}. \qquad (1.35)$$

It is necessary to give attention to the fact that in (1.34) there is no factor which takes into account the exponential damping in the metal inasmuch as the material is electrically thin. The effectiveness also does not depend on the frequency, but is determined by the conductivity and thickness of the shield material. Considering that the surface resistance per unit area $R_0=\rho/d$ ohm, we represent (1.34) in the form

$$\Э'_{0пл}=60\pi/R_{\square}. \qquad (1.36)$$

It is convenient to use formula (1.36) when the surface resistance is known and the material thickness is unknown, which takes place on metal coating of the surface or the application of a current-conducting paint. The resistance $R_{\square}$ is determined on direct current by the volt meter and ammeter method.

Let us represent (1.35) in the logarithmic expression:

$$\Э_{пл}=36+20\lg(\delta/\rho)+8,7(d/\delta). \qquad (1.35')$$

In this formula 8.7 (d/δ) takes into account the losses to absorption, and the remaining terms (36 and $20\lg(\delta/\rho)$),the losses to reflection.

Using (1.29), let us represent the shielding effectiveness of the plane wave as a result of reflection in the form

$$\Э_{отр}=5,5+10\lg(\lambda\sigma/\mu_r). \qquad (1.37)$$

The presented formulas do not permit determination of the effectiveness of the closed shield, for the field inside it is distinguished by nonuniformity of distribution, complexity of structure and has a number of peculiarities by comparison with the electromagnetic field formed by a plane wave in free (open) space.

In [19] it is demonstrated that the shielding effectiveness of the shield components under idealized conditions by a shield of spherical shape can be calculated by the formulas

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$$\mathcal{E}_{0E} = 0{,}21\frac{\lambda}{R_э}\mathcal{E}_{0пл},\quad \mathcal{E}_{0H} = 4{,}2\frac{R_э}{\lambda}\mathcal{E}_{0пл}, \qquad (1.38)$$

where $R_э$ is the equivalent radius of the shield, meters.

The coefficients for $\mathcal{E}_{0пл}$ become equal to one for $\lambda \approx 1{,}5\pi R_э$, when the shielding conditions of the plane wave occur. In this load the shielding effectiveness of the field components is identical.

Electromagnetic shields can be calculated still with sufficient accuracy only in certain idealized cases. These include the following:

An infinitely flat shield on the propagation path of a plane wave;

Placement of a point source in the center of a sealed, ideally conducting shield of spherical shape;

An infinitely long ideally conducting cylinder with emitter in the form of infinite filament located on the axis of this cylinder.

All of these cases fail to reflect the actual operating conditionsof the shield, inasmuch as they do not take into account the relations between the wave length and the linear dimensions of the shield, the nature of the source, the nonuniformity or distribution of the field inside the shield, the nonuniformity of the material and the structural design of the shield itself and, primarily, the possibility of the penetration of the field through the slits and openings occurring in the real shield. In addition to the indicated factors, the effectiveness of a real flat shield depends on the type of material and structural design, its thickness, the nature and number of holes and slits in the shield. Obtaining the analytical expression for calculating the thickness of a shield considering the indicated factors and parameters encounters unresolved mathematical difficulties. The introduction of the existing restrictions will lead to excess idealization of the problem itself and solution.

As is known, one of the most expedient problem-solving means in engineering practice, which contains a large number of uncontrolled factors and parameters, different explicit and implicit functional relations, is the use of statistical methods. It is necessary to resort to these methods also when estimating the effectiveness of real shields. In particular, the results obtained by the author when processing the materials from testing a large number of different electromagnetic shields, the quality of which turned out to be no less than the admissible level, demonstrated that their effectiveness is only 0.1...0.2 of the potentially powerful effectiveness expressed in decibels.

A procedure is presented below (§2.9) for approximate calculation of the effectiveness of real shields.

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1.5. Shielding as a Volumetric Resonator

Just as in any closed space, the process of the movement of electromagnetic energy in the shield is accompanied by a number of phenomena which include the following:

The accumulation and absorption of energy; the reflection of electromagnetic waves and redistribution of the electromagnetic fields;

Resonance phenomena; the reaction of the shield to the shielded devices;

The radiation of electromagnetic energy through the openings and slits in the shield; the penetration of external electromagnetic fields into the shield.

These phenomena can occur on location of the emitter (source) of the electromagnetic oscillations both inside and outside the body of the shield. For analysis the case is more convenient where the source is located inside the shield. Therefore the external field source is expediently represented by the internal emitter equivalent to it.

Each of the indicated phenomena can to a defined degree lead to violation of the operating conditions of the shield, that is, to an inadmissible reduction in its effectiveness. Depending on the purpose and structural design of the shield, the effect of the indicated factors will be different: some will have a predominant effect, and others, a secondary effect; it is in practice possible to neglect the consequences of the third group.

A shield as a volumetric resonator has distributed parameters, the values of which are determined by its shape and size, the thickness and properties of the material and the structural peculiarities. For simplification let us assume that the shield is a parallelepiped (see Fig 1.11), the length of which is ℓ, the width is b and the height is h.

A generalized parameter characterizing the shield dimensions is the equivalent radius

$$R_э = \sqrt[3]{\frac{3}{4\pi} blh} \approx 0{,}62 \sqrt[3]{V_{экр}}, \quad (1.39) \quad (1)$$

Key: 1. Shield

where V_{shield} is the inside volume of the shield, m^3.

If the sides of the parallelepiped are in the "golden cross section" ratios of 8;5;3 for which the most uniform field distribution E(H) is observed inside the shield, then

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$$b^2=hl;\quad h+b=l,$$
$$h=0{,}62\sqrt[3]{V_{\text{экр}}};\quad b=\sqrt[3]{V_{\text{экр}}};\quad l=1{,}62\sqrt[3]{V_{\text{экр}}},\ (1)$$
$$S=bl=1{,}62V^{3/2}_{\text{экр}};\quad \Sigma S=6{,}5\sqrt[3]{V_{\text{экр}}}, \qquad (1.40)$$
$$(1)$$

Key: 1. shield

where ΣS is the total surface of the shield.

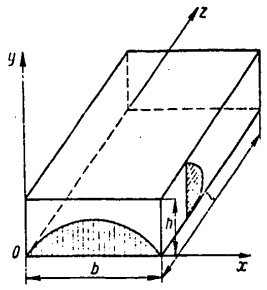

Figure 1.11. Basic type field distribution in a resonator

When the "golden cross section" rule is satisfied, then, as follows from (1.40), $R_э=h$.

As is known, the capacity of a resonator to accumulate electromagnetic field energy is estimated by its own Q-factor:

$$Q=\omega_0\frac{W}{P_п}=\frac{\omega_0 L_э}{R_{\omega э}}, \qquad (1.41)$$

where ω_0 is the resonance frequency; W is the energy stored in the resonator; $P_п$ is the power of the losses dispersed in the resonator; $L_э$ is the equivalent inductance of the resonator; $R_{\omega э}$ is the total resistance of the resonator losses.

For the given intensity of the electric and magnetic fields, the amount of energy stored in the resonator is proportional to its volume V_{shield}, and the power of the losses is proportional to the volume of the surface layer $\delta\Sigma S$ in which the losses occur. Therefore

$$Q\approx V_{\text{экр}}/\delta\Sigma S. \qquad (1.42)$$

Consequently, the Q-factor of the closed shield as a resonator is proportional to its volume and inversely proportional to the depth of penetration of the field and to its metal surface. In the ideal case the Q-factor

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is large. It is larger for nonmagnetic materials in which δ is larger, but the loss is smaller.

The electromagnetic energy stored by the resonator [20]

$$W = \frac{\varepsilon}{8} E^2 V_{экр}, \qquad (1.43)$$

where ε is the dielectric constant of the medium inside the resonator; E is the field intensity inside the resonator.

Depending on the radiation power, the energy stored by the resonator can be significant; then E reaches larger values. On the other hand, by analogy with an acoustic field in a closed space where the wave length is less and is commensurate with the linear dimensions of the resonator, the standing wave energy can be determined from the expression [21]

$$W = \frac{P}{\Sigma S} \frac{4R_0}{(1 - R_0)\, c} V_{экр}, \qquad (1.44)$$

where V_{shield} is the resonator volume; P is the power of the emitter; R_0 is the reflection coefficient of the surface of the resonator; c is the propagation rate of the electromagnetic wave.

From (1.43) and (1.44) we find the field intensity in the resonator

$$E \approx \sqrt{\frac{32 P R_0}{c \varepsilon \Sigma S (1 - R_0)}}.$$

For air when $\varepsilon = 8.85 \cdot 10^{-12}$ farads/m, we obtain

$$E\left[\frac{\text{В}}{\text{м}}\right]_{(1)} \approx 110 \sqrt{\frac{P R_0}{(1 - R_0)\, \Sigma S}}. \qquad (1.45)$$

Key: 1. E[volts/m]

If the shield dimensions greatly exceed the wave length, this leads to nonuniform distribution of the field inside it. At individual points of the inside space, especially at the nodes, significant field concentration can be observed, at the same time as in other parts of the shield the field will be attenuated. The slits and openings in the shield lead to an additional decrease in stored energy. Therefore in the general case formula (1.45) is approximate. In addition, the field intensity determined by expression (1.45) characterizes only one part of the total field in the closed shield -- the diffuse field by which we mean the field occurring under stationary conditions after multiple reflections inside the resonator. The second term is the direct wave field. Thus, the total electromagnetic energy

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$$W_{\text{об}}=W_{\text{отр}}+W_{\text{пр}}.$$
(1) (2) (3)

Key: 1. total; 2. reflected; 3. direct

At frequencies above 100 megahertz usually the power flux density is considered. In a diffuse field the power flux density is

$$\Pi_{\text{отр}}=\frac{P}{\Sigma S}\frac{4R_0}{1-R_0},$$
(1)

Key: 1. reflected

and the power flux density of the incident wave $\Pi_{direct}=PG/4\pi r^2$. The total power flux density in the resonator

$$\Pi_{\text{об}}=\Pi_{\text{отр}}+\Pi_{\text{пр}}=\frac{PG}{4\pi r^2}+\frac{P}{\Sigma S}\frac{4R_0}{1-R_0}, \qquad (1.46)$$
(1) (2) (3)

Key: 1. total; 2. reflected; 3. direct

where P is the mean radiation power; R_0 is the reflection coefficient; G is the amplification coefficient of the antenna (emitter) in the given direction; r is the distance to the source (emitter);

As is obvious from (1.46), the power flux density in the incident wave is a function of the distance to the source and its intensity as an emitter, and the equivalent reflection power flux density is distributed almost uniformly over the entire volume. In the absence of the absorbing material inside the shield the field power in the resonator can be many times greater than the power of the source as a result of accumulation of the power. On absorption of the field inside the shield the power flux density also receives an increment which is defined by the quality of the absorbing material and is analytically caused by the factor $4R_0/(1-R_0)$. This factor is very large for R_0 close to one; for $R_0=0.2$ it becomes equal to one, and then the equivalent flux density of the reflected power is a function only of the total surface of the shield. For $R_0\leq 10^{-3}$ the factor $4R_0/(1-R_0)\leq 0.004$ and, consequently, the total field is determined only by the incident wave.

The accumulation of the electromagnetic wave energy in the shield just as in the volumetric resonator is one of the most significant factors which must be considered both when designing the shielding system and during the course of its operation. The effect of this factor on the functioning of the shield and the objects located inside is determined by the reduction in shielding effectiveness, the danger of breakdown of the dielectric inside the shields, the effect of the field on the shielded devices, the effect of the electromagnetic field on the operator in the shielded space.

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In order to insure normal functioning of the shield at fixed power of the emitter it is necessary to select ΣS, R_0 and r correctly. The possibility of varying the value of r is determined from the relation between the power flux density of the incident wave and the diffuse field:

$$A = \frac{\Pi_{пр}^{(1)}}{\Pi_{отр}} = \frac{G\Sigma S(1-R_0)}{16\pi r^2 R_0}.$$
(2)

Key: 1. direct; 2. reflected

Equating this ratio to one, we find the distance to the emitter for which the power flux density of the direct wave is equal to the power flux density of the diffuse field:

$$r_{гр}^{(1)} = 0{,}14\sqrt{G\Sigma S(1-R_0)/R_0}. \qquad (1.47)$$

Key: 1. limit

If $r<r_{limit}$, the power flux density is basically determined by the incident wave, and for $r>r_{limit}$, by the diffuse field. In a steel shield for a point source when $R_0=0.99$, $\Sigma S=100$ m^2, we have $r_{limit}=0.14$ meters. Incidentally, in this case only in the direct proximity to the source ($r<0.14$ m) is the power flux density determined by the direct wave. In a real shield, as a result of the presence of slits and openings the power flux density of the diffuse field decreases, as a result of which r_{limit} increases, and in practice the power flux density of the direct wave is measured at distances not exceeding 0.3 meters.

When designing shields for powerful sources, in addition to considering the field distribution it is necessary to take measures to decrease the losses in the shield. The losses in the shield are created as a result of eddy currents flowing through the shield and causing heating of it. The intensity power losses in the shield can lead to significant overheating of it, to melting, in particular, when shielding powerful electromagnetic shields. It is assumed that the shield must have dimensions and a structural design and be made of a material such that the losses will not exceed 1% of the emission power.

The losses in the resonator can be determined from (1,41) and (1.42)

$$P_{п}^{(1)} = \omega_0 W \delta \frac{\Sigma S}{V_{экр}}. \qquad (1.48)$$
(2)

Key: 1. losses; 2. shield

In real shields the losses to the eddy currents for a point source can be determined by the empirical formula

$$P_{п}^{(1)} = 8\frac{P_{изл}^{(2)}}{3\sqrt{V_{экр}}}\sqrt{\frac{\mu_r f}{\sigma}}, \qquad (1.49)$$
(3)

Key: 1. losses; 2. emission; 3. shield

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where P_{losses} are the losses in the shield, watts; $P_{emission}$ is the emission power, watts; V_{shield} is the volume of the shield, m^3; μ^r is the relative magnetic permeability of the shield material; f is the frequency, megahertz; σ is the conductivity of the shield material $(ohms\text{-}meter)^{-1}$.

For a cylindrical shield shielded with the coil of a powerful oscillatory circuit, the power of the losses is determined by the expression [22]

$$\underset{(1)}{P_{\text{п}}}=\frac{2\pi n^2 I^2 r_{\text{ш}}^4 (3)}{l_{\text{к}} r_{\text{ш}}^2 s_{\text{ш}} \sigma \delta}, \qquad (1.50)$$
$$(2)\ (2)$$

Key: 1. losses; 2. shield; 3. coil

where n is the number of turns in the coil; I is the effective value of the current in the coil; r_{shield} is the radius of the shield; r_k is the coil radius; ℓ_k is the length of the coil.

When shielding oscillatory circuits, the losses in the shield can be represented as an equivalent additional resistance in the oscillatory circuit influencing its primary and secondary parameters. As a result, the mutual effect of the shielded object on the shield and vice versa takes place. This mutual effect can be greater the closer the shield is located to the shielded object. It is exhibited in an increase in the active resistance and the capacitance of the circuit, in a decrease in its inductance and Q-factor.

The initial parameters of the coil (without shield) shielded by a cylindrical shield vary by the amounts $\Delta L=-\beta_L L_0$ and $\Delta R=\beta_R R_H$ as a result of the reaction of the cylindrical shield for comparatively small increments, where the coefficients β_L, $\beta_R \geq 0$, in essence being the moduli of the derivatives of the corresponding functions, depend on the shield material, the frequency, the ratios of the coil diameters to the shield diameter and length of the coil to the shield length.

Any type of electric wave set up in the oscillation process in the resonator must be such that the electric field intensity on the walls will be equal to or close to zero, and accordingly the wave must be set up across the resonator (see Fig 1.11). The same electric field intensity distribution can occur when the wave moves along the z-axis. The resonator can turn out to be tuned to resonance if an even number of halfwaves are set up along the edge b. In the rectangular resonator there can be oscillations of different types distinguished from each other by the field distribution and frequency. Each type of oscillation corresponds to its own resonance frequency and, consequently, the shield as a volumetric resonator is characterized by a set of resonance frequencies. As is known, the resonance wave length of the resonator for oscillations of the type of $TE_{m,n,p}$ and $TM_{m,n,p}$ is:

$$\underset{(1)}{\lambda_{\text{рез}}}\ [\text{м}]=2/\sqrt{(m/l)^2+(n/b)^2+(p/h)^2}=300/\underset{(1)}{f_{\text{рез}}}, \qquad (1.51)$$

Key: 1. resonator

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where ℓ, b, h are the dimensions of the sides of the resonator; m, n, p are the indexes denoting the number of standing halfwaves set up along the edges of the resonator; $f_{resonator}$ is the resonance frequency, megahertz.

Let us define the resonance frequencies in wave lengths for different types of oscillations. We shall solve the problem in the following order:

a) Let us determine the coefficients $M=\pi m/\ell$, $N=\pi n/b$, $P=\pi p/h$;

b) Let us find the phase coefficient $\alpha=\sqrt{M^2+N^2+P^2}$;

c) Let us determine the resonance frequency

$$f_{рез}=\frac{c\alpha}{2\pi}=\frac{c}{2\pi}\sqrt{M^2+N^2+P^2}$$
(1)

Key: 1. resonator

and the resonance wave length

$$\lambda_{рез}=\frac{2\pi}{\alpha}=\frac{2\pi}{\sqrt{M^2+N^2+P^2}}.$$

The results of the calculations in general form are presented in the table (see Table 1.1). As is obvious from the table data, the lowest type of transverse magnetic oscillations corresponding to the first values of m, n and the least value of the natural frequency $f_{resonance}$ is the TE_{110} type. When calculating the resonance frequency it is proposed that the sides ℓ and b are the larger resonator sides. As a rule, first of all it is necessary to determine the lowest resonance frequency for the given shield dimensions, for the occurrence of resonance in the shield is accompanied by a sharp increase in the field amplitude and when using an electrically thin material for the shield, intensive decay of its effectiveness is observed.

The least resonance frequency of the shield is conveniently calculated not as a function of the dimensions of the sides of the shield, but as a function of its largest total parameter R_{shield} by the approximate formula

$$f_{resonance}\approx 138/R_{shield}, \text{ megahertz}, \qquad (1.51')$$

where R_{shield} is the equivalent radius of the shield, meters.

The Q-factor of the resonator for oscillations of the TE_{110} type can be determined from (1.42);

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$$Q_{TE_{110}} \approx \frac{V_{экр}^{(1)}}{\delta \Sigma S} \approx \frac{0,5}{\delta (1/l + 1/b + 1/h)}. \qquad (1.52)$$

Key: 1. shield

For example, for a shield made of steel, the sides of which are l=3 m, b=2 m and h=1 m when operating it on a frequency of f=30 megahertz and $\delta = 3 \cdot 10^{-6}$ meters, we have

$$Q_{TE_{110}} \approx \frac{0,5}{\delta\left(\frac{1}{l}+\frac{1}{b}+\frac{1}{h}\right)} = \frac{0,5 \cdot 10^6}{3\left(\frac{1}{3}+\frac{1}{2}+1\right)} = 3 \cdot 10^5.$$

The actual Q-factor as a result of the presence of openings and slits will be one to two orders less than calculated.

The width of the resonance curve is

$$2\Delta f = \frac{f_{рез}^{(1)}}{Q} = \frac{106}{R_э Q} = \frac{106}{0,62 \cdot 1,8 \cdot 3 \cdot 10^5} = 3 \cdot 10^{-4} \text{ МГц}. \quad (2)$$

Key: 1. resonance; 2. megahertz

The resonance frequencies of real shields do not always correspond to the calculated ones, for as a result of the presence in the shield of certain objects, its resonance frequency shifts. Usually for the shields of radio-electronic equipment and radio-electronic devices widespread in practice, the resonance frequencies are about 30...1000 megahertz. With an increase in the shield dimensions the resonance shifts in the direction of the lower frequency, as is obvious from (1.51').

At resonance the field intensity inside the closed shield increases by Q times, and, consequently, the shielding effectiveness decreases by Q times with respect to the resultant effectiveness taking into account the absorption in reflection of the electromagnetic waves. For electrically thin materials, the effect of the shielding of which is manifested only as a result of reflection, the shielding effectiveness at resonance will become highly insignificant. In shielding practice this phenomenon quite frequently is observed and illustrated by the graphs (see Fig 1.12). Here the effectiveness of the shields from the lowest resonance frequency is demonstrated as a function of the thickness of the shield material d and the equivalent radius of the shield $R_э$. As is obvious from the indicated graphs, for example, the application of aluminum 0.02 mm thick for $R_э$=2,3 meters on a resonance frequency of 60 megahertz gives shielding effectiveness of no more than 20 decibels in spite of the fact that

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Table 1.1

Frequencies of the natural oscillations for different types of waves

Types of waves		TE_{110}	TE_{101}	TM_{011}	TM_{111}, TE_{111}
Characteristic numbers	m	1	1	0	1
	n	1	0	1	1
	p	0	1	1	1
Coefficients	M	π/l	π/l	0	π/l
	N	π/b	0	π/b	π/b
	P	0	π/h	π/h	π/h
Phase coefficient α		$\pi\sqrt{\left(\frac{1}{l}\right)^2+\left(\frac{1}{b}\right)^2}$	$\pi\sqrt{\left(\frac{1}{l}\right)^2+\left(\frac{1}{h}\right)^2}$	$\pi\sqrt{\left(\frac{1}{b}\right)^2+\left(\frac{1}{h}\right)^2}$	$\pi\sqrt{\left(\frac{1}{l}\right)^2+\left(\frac{1}{b}\right)^2+\left(\frac{1}{h}\right)^2}$
Freqency of the natural oscillations of the resonator $f_{resonator}$, megahertz		$150\sqrt{\left(\frac{1}{l}\right)^2+\left(\frac{1}{b}\right)^2}$	$150\sqrt{\left(\frac{1}{l}\right)^2+\left(\frac{1}{h}\right)^2}$	$150\sqrt{\left(\frac{1}{b}\right)^2+\left(\frac{1}{h}\right)^2}$	$150\sqrt{\left(\frac{1}{l}\right)^2+\left(\frac{1}{b}\right)^2+\left(\frac{1}{h}\right)^2}$
Resonance wave length λ, meters		$\frac{2}{\sqrt{\left(\frac{1}{l}\right)^2+\left(\frac{1}{b}\right)^2}}$	$\frac{2}{\sqrt{\left(\frac{1}{l}\right)^2+\left(\frac{1}{h}\right)^2}}$	$\frac{2}{\sqrt{\left(\frac{1}{b}\right)^2+\left(\frac{1}{h}\right)^2}}$	$\frac{2}{\sqrt{\left(\frac{1}{l}\right)^2+\left(\frac{1}{b}\right)^2+\left(\frac{1}{h}\right)^2}}$

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outside resonance of the same shield will have effectiveness of more than 100 decibels. Therefore a mandatory condition of the use of electrically thin materials is preliminary determination of whether the magnitude of the decrease in effectiveness in the resonance band is within the admissible limits.

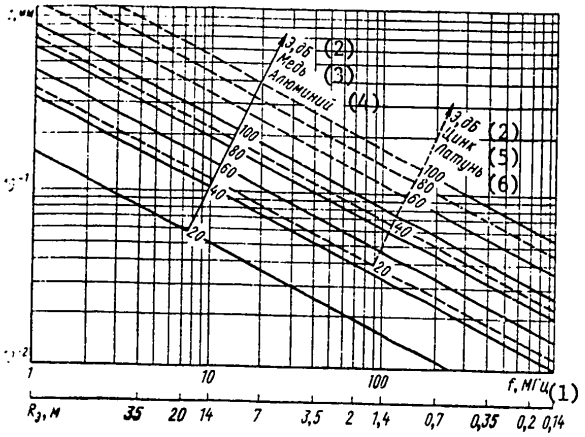

Figure 1.12. Shielding effectiveness on the lowest resonance frequency of the shield as a function of its parameters

Key:

1. f, megahertz
2. decibels
3. copper
4. aluminum
5. zinc
6. brass

Physically the decrease in effectiveness on resonance frequency can be explained by a decrease in reflection, which is caused by penetration of the shield beyond the shield limits. It is obvious that under resonance conditions (longitudinal or transverse) the reflecting surfaces will become transparent, which is possible when the shield thickness becomes equal to the integral number of halfwave lengths in the material, that is,

$$d=m\lambda_м/2, \qquad (1.53)$$

where m is a positive integer; λ_M is the wave length of the material.

Inasmuch as the wave length in the metal is determined by the expression [17] $\lambda_M=2\pi\sqrt{2/\omega\mu_r\sigma}=2\pi\delta$ and in order to exclude the effect of resonance $d>0.5\lambda_M>\pi\delta$, the thickness of the shield material thus becomes dependent on its type and the linear dimensions.

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The maximum reflection from the shield walls takes place for $d=\lambda_M/4$.

When using lattice materials they must be checked analogously with respect to the equivalent thickness determined by the formula $d_z=\pi r_s^2/s$, where r_s is the radius of the grid wire; s is the grid spacing.

The physical phenomena observed in a closed shield, just as in a volumetric resonator, must always be taken into account when building actual shields.

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CHAPTER 2. BASIC STRUCTURES OF ELECTROMAGNETIC SHIELDING FOR RADIO-ELECTRONIC EQUIPMENT

2.1. Structural Characteristics of Electromagnetic Shielding

Modern radio-electronic equipment is distinguished by great complexity and consistent set of elements, the interaction between which must occur with respect to strictly defined channels and circuits. The appearance of any other areas of interaction of the radio-electronic elements disturbs the normal operating conditions of the equipment.

One of the basic methods of eliminating the mutual couplings not provided for by the functional diagram is element by element, block and total shielding of the radio-electronic equipment. In this sense the shielding plays an auxiliary role, and the design of the shields depends on their specific purpose. If when developing the radio-electronic means the overall intent of the designer, the location and composition of the equipment parts do not take into account the necessity for shielding, then the design problems caused by this turn out to be in a subordinate position, which frequently leads to insurmountable difficulties. If the suppression of undesirable spurious couplings between the radio-electronic elements is one of the basic design conditions, then the shielding takes on a leading role, which promotes more effective and higher quality solution of the basic problem.

Thus, the design of electromagnetic shields can have the following characteristics.

First, it can consist in the following independent shield designs. Then the shield is in the form of an outside jacket for the equipment and must provide for thermal conditions, protection from dust and moisture, vibration resistance, attenuation of the effect of external electromagnetic field on the device as a whole, or localization of its electromagnetic emissions.

Secondly, shield designs can be developed for individual elements and assemblies of the radio-electronic equipment when the dimensions and even the shape of the shield in practice are determined by the shielded object itself. In the given case the shield must be inscribed in the overall

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device, it must insure minimum reaction to the shielded object, repair suitability and normal operating conditions of the radio-electronic equipment.

Finally and thirdly, the design problem can consist in the development of electromagnetic shields as independent structures not connected with any individual type of radio-electronic means and design for protection against external fields or localization of the radiation of the overall radio-electronic complex, for taking special measurements under the conditions approaching the conditions of free space, for the assembly and the adjustment of equipment, and so on.

The solution of the problem with respect to shield design, depending on purpose, has its specific nature caused by the volume of operations and sequence of selections.

If the shield is an external jacket of the equipment, it determines the overall composition, external appearance and operating conditions of the radio-electronic equipment. This case is the most common, for here the problems of block and element-by-element shielding and filtration of the circuits must be solved with maximum use of the standardized and normalized products and also products from other equipment assimilated by production. The design must be made considering the characteristics of the given type of radio-electronic equipment. The achievement of simplicity of the structural design of the shield must be combined with its compactness, exclusion of excessive breakdown of the overall design into individual modules, insurance of simplicity of manufacture, high cost benefit and improvement of operating qualities, convenience of servicing and repair of the radio-electronic equipment and also the satisfaction of the requirements of engineering psychology and esthetics. From these points of view it is important to select the shielding material and its coatings properly, which determines the technological characteristics of the equipment, its individual devices and their operatingconditions. The requirements imposed on the shielding follow from the general requirements on the radio-electronic equipment and the role given to the external housing of the device.

In the latter case the technical requirements on the shielding are still more caused by the shielding elements. Here the requirement of maintenance of the required effectiveness is defining.

In the third case, the shield is an independent structure, for example, a shielded facility, the operations are performed on the basis of the planning assignment in which the following problems must be solved:

The required effectiveness of the shielding in the given frequency band is established;

The materials for the shield, its dimensions, the number and type of door and window openings are selected;

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The version of the arrangement of the equipment is selected which insures minimum noise level and simplicity of filtration of the interference-carrying network;

The structural design of the basic assemblies is determined: the methods of joining the shielding shape, fastening the shielding to the walls, the floor, the ceiling, the structure of the contact system, the methods of shielding the ventilation systems and the entries of the various communication lines;

The types and number of cables introduced into the shield are established, the types of filters and points of their installation are selected, and the branch points of the electric circuits are made;

The methods of laying and introducing the unfiltered high-frequency cables and cables carrying nonsinusoidal currents or voltages are selected.

One of the basic causes of the appearance of mutual interference is insufficient attention to the problems of shielding and filtration of the radio-electronic equipment and other electrical devices. This can be confirmed at least by the fact that the technical requirements on the radio-electronic devices frequently do not contain specific requirements with respect to limiting emissions and external interference suppression. Moreover, it is known that the side and extraband emissions and reception channels with insufficient shielding effectiveness occur not only through the antenna-feeder system, but also through various openings, slits in the structures of the radio-electronic equipment and the opened (unshielded) feeder lines. The insufficient consideration of the indicated facts essentially lower the effectiveness of developing the radio-electronic equipment as a whole.

The solution of the general or partial technical problem with respect to electromagnetic shielding usually begins with the study of the radio device, as a result of which the sources are discovered and the most economical means of attenuating the radio interference are planned. These methods can provide for the following:

Introduction into the circuits, the design and placement of the equipment assemblies, additional elements and changes providing for a decrease in interference levels to minimum values as a result of the influence both on the interference source and on the paths of propagation of the interference;

Protection of the most sensitive elements of the radio-electronic equipment from the effect of interference by partial or complete shielding;

Localization of the interference at the points of its generation or in the volumes from which these most sensitive elements of radio-electronic equipment or the equipment itself are excluded.

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It is natural that the interference in the circuit and the basic design of the equipment must be minimal and justified from the point of view of changing its technical and economic indexes after shielding. Thus, after analyzing the schematic diagram and the structural design of the radio-electronic equipment, the question of selecting the shielded spaces, circuits and elements is decisive. When designing the shield itself, the designer must consider measures with respect to its electrical (and mechanical, if required) seal and the continuity of the shielding, cooling and ventilation, the introduction and exit of the communications, filtration of the feed circuits, the signal and control circuits.

With all the apparent simplicity of the structure of the electromagnetic shield, their technical realization frequently gives rise to defined difficulties. This is caused by the significant divergence of the calculated data by comparison with the experimental data in the absence of sufficiently substantiated methods of testing the shields in a wide frequency band. Inasmuch as in many cases the shielding and filtration system is a complicated complex of closed and open flat shields, wave guide filters, electric filters and other elements, the final finishing of the structural design must take place on a model. However, with efficient placement of the parts and elements of the shielding system in accordance with the calculated data, the corrections introduced into the design usually are insignificant.

The leading operating design document is schematic diagram of the shielding system on which the noise forming and emitting elements must be isolated with estimation of the interference levels and the susceptible (sensitive) elements with indication of the admissible values of the induced interference emf and the degree of required attenuation. The diagram of the mutual coupling of the element and the assemblies obtained in this way is drawn up successively throughout the entire work and changes as satisfactory results are achieved in different design phases. It is obvious that with the same initial data a defined number of versions of such systems can be obtained, which depends on the complexity of the problem and the experience of the designer. On the whole, it must lead to the optimal technical solution. It must be noted that unsubstantiated rejection of any of the versions or refusal to consider any factor determining the interference intensity under the assumption that the corresponding correction will be made when installing the device frequently leads to a delay in executing the design of the shielding system, putting the radio-electronic equipment into operation and excessive expenditures of means. As a result, the required shielding effectiveness cannot be insured.

2.2. Materials for Shields

For a long time in electromagnetic shielding engineering only the so-called "traditional" materials were used -- metal sheets. This is explained primarily by the fact that the high conductivity provides for rapid damping of electromagnetic energy in the body of the metal, and great distance between the surface resistance of the metal and the total resistance of the

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incident wave leads to significant reflections of the radio waves from the surface of the shield. As a result, the metal sheet of insignificant thickness has high shielding effectiveness. However, the practice of shielding indicates that the extraordinarily high effectiveness of the metal itself actually is only 10 to 20% realized inasmuch as the primary factor here is the quality of the design. Questions about the expediency of applying highly effective materials having comparatively high cost which do not insure the required size and weight characteristics and the form of the structural designs required from the point of view of the shielding and other conditions naturally arise. Therefore in many cases it turns out to be possible to replace a metal shield with a shield made up of other material. This possibility also arises from the assimilation of a number of new materials. The necessity of obtaining the required effectiveness, the problems of insuring mobility of the design, simplification of its assembly, reduction of costs, and so on have created prerequisites for the application of new materials, the natural capacity of which for shielding electromagnetic fields can also not be very high.

Metal materials are selected from the following conditions:

Achievement of the given magnitude of attenuation of the electromagnetic field and its components in the operating frequency range with corresponding restrictions of the shield dimensions and its effect on the shielded object;

Resistance to corrosion and mechanical strength;

Technological nature of the shield design and obtaining of the required configuration in weight and size characteristics.

The first requirement is in practice satisfied by all of the sheet material used at the present time (steel, copper, aluminum, brass), for with corresponding thickness of them they insure sufficiently high shielding effectiveness.

If we consider the shielding effectiveness by magnetic and nonmagnetic materials of identical thickness as a function of frequency, then for the different frequency ranges the shielding properties will be different. Until the shield operates under magnetostatic conditions, the effectiveness of the magnetic materials is appreciably higher than nonmagnetic materials. Under electromagnetic conditions, in the frequency band where the shielding effectiveness as a result of reflection is greater than the absorption effectiveness, the nonmagnetic materialshaving greater conductivity by comparison with the magnetic material insure higher effectiveness. In the frequency range where the shielding properties are exhibited more as a result of absorption, the effect of the nonmagnetic materials on the total shielding effectiveness increases. However, in real shields the indicated properties of the magnetic and nonmagnetic materials are poorly manifested. The predominant application of steel here is determined by the economicalness and technological nature of the design.

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The advantages of steel are lost when shielding current-carrying elements which are critical to the losses introduced into them. For example, under other equal conditions, comparing the losses of power in the shields made of steel and copper, assuming in this case that $d>>\delta$, we obtain

$$\frac{P_{ст}^{(1)}}{P_{м}^{(2)}}=\frac{\sigma_м\delta_м}{\sigma_{ст}\delta_{ст}}=\sqrt{\frac{\sigma_м}{\sigma_{ст}}\mu_r}. \qquad (2.1)$$

Key: 1. steel; 2. copper

From (2.1) it follows that since $\sigma_{copper}>\sigma_{steel}$ and $\mu_r>>1$, the losses in the steel are always higher. For example, for $\mu_r=50$ the power losses in the steel shield will be approximately 18 times greater than in the copper shield. Thus, as a result of the high losses introduced by the steel shields, their application is basically limited.

When shielding high-frequency oscillatory circuits and other circuits by cylindrical shields with the condition that the losses of the oscillatory power do not exceed 1%, the shield radius, as follows from [23], must be no less than

$$R\geqslant 8{,}5r_к\sqrt[3]{\frac{n^2I^2}{\sigma\delta(l_к/r_к)P}}, \qquad (2.2)$$

where r_k is the coil radius, meters; ℓ_k is the length of the coil, meters; n is the number of turns of the coil; I is the coil current, amps; σ is the specific conductivity of the shield material, $(ohm\text{-}m)^{-1}$; P is the generator power, watts; δ is the depth of penetration.

If in this case under other equal conditions we use steel and copper shields, then the ratio of their radii must be

$$\frac{R_{ст}^{(1)}}{R_{м}^{(2)}}=\sqrt[3]{\frac{\sigma_м\delta_ч}{\sigma_{ст}\delta_{ст}}}=\sqrt[6]{\frac{\sigma_ч}{\sigma_{ст}}\mu_r}. \qquad (2.3)$$

Key: 1. steel; 2. copper

Since usually $\sigma_{copper}>\sigma_{steel}$, and $\mu_r>>1$, then $R_{steel}>R_{copper}$ and the overall dimensions of the steel shield turn out to be greater than copper. For example, if $\mu_r=50$, then for the same losses the radius of the steel shield must be approximately twice the radius of the copper shield. The results of comparing the steel with other nonmagnetic materials from the point of view of their use in electromagnetic shielding of high-frequency coils with high Q-factor look approximately the same. These results turn out to be valid for shields of any shape reduced in the general case to the equivalent cylinder or sphere.

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The dissipated power usually decreases with an increase in the equivalent radius $R_э$ of the shield. If it is necessary to decrease the losses of the given $K_э$ or to decrease $K_э$ for the given losses, then it is necessary to make the shield of copper or aluminum.

For electromagnetic shielding, thin-sheet and foil materials 0.01 to 0.05 mm thick can be used which are made of diamagnetic materials. The shields made of the indicated materials have sufficient shielding effectiveness. It is necessary, however, to note the possibility of the occurrence of resonance phenomena for which the effectiveness decreases sharply.

As for insuring resistance to corrosion and mechanical strength, this requirement can be satisfied in practice by all the materials when using protective coatings. This requirement is also satisfied by all types of screens. Foil materials are also resistant to corrosion, but their mechanical strength is still inadequate. Therefore the application of these materials is limited to cases where they can be coated with protective coatings which prevent damage to the layer or when the operating conditions of the shields do not require mechanical strength of it.

The most technological are the shield designs of steel inasmuch as on installation of the shield it is possible to make broad use of welding.

Practice has shown that in a wide frequency band in order to insure shielding effectiveness of 100 decibels and more it is expedient to use sheet steel with the exception of the cases where the restrictions investigated above have decisive influence.

The thickness of the steel is selected beginning with the type and purpose of the design, its installation conditions and, primarily, the possibility of realizing continuous welds. When welding on alternating current the thickness is selected at approximately 1.5 to 2 mm; on direct current, it is about 1 mm, and for gas welding, 0.8 mm.

The screen materials are widely used for the construction of shields for various purposes. This is explained by the fact that the metal screens are light, and the screen shields are simpler to manufacture, they are convenient to assemble and in operation, they insure sufficient air exchange, they have light permeability, and they make it possible to obtain sufficiently high effectiveness in the entire radio frequency band. The deficiencies of the screen materials include the following: low mechanical strength and loss of effectiveness as a result of aging. The second deficiency can be eliminated with the corresponding operation of the shield.

It has been considered for a long time that the decrease in shielding effectiveness as the screen ages is caused by disturbance of the contact at the nodes of its cells as a result of corrosion and contamination, which leads to an increase in the spacing. The studies have demonstrated that

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the shielding effectiveness by the screen almost does not depend on the quality of contact in itself. The disturbance of the direct contact between the wires of the individual cells does not decrease the overall effectiveness on low frequencies. On high frequencies the disturbance of the contact between the cell wires is compensated for by small transitional capacitive resistances.

A decrease in effectiveness can occur as a result of corrosion. Therefore in order to protect the screen against corrosion it is expedient to coat it with anticorrosion lacquer.

The shielding properties of the metal screens are exhibited primarily as a result of the reflection of an electromagnetic wave from their surface. The parameters of the screen defining its shielding properties are as follows: screen spacing s equal to the distance between adjacent centers of the wire, wire radius r and specific conductivity of the screen material.

Dense and sparse screens are distinguished. The former include the screens for which $s/r \leq 8$, and the latter, $s/r > 8$.

The shielding effectiveness of the screen materials is as follows [24]

$$\vartheta_{\bullet} = \frac{\lambda}{2s\,[\ln (2\pi r/s)]},$$

the results which this formula provides agree well with the results of the measurements only for sparse screens; for dense screens the calculations turn out to be somewhat high. The latter is explained by the fact that for dense screens the value of $\ln (s/2\pi r)$ determines the inductance of the cell. With a decrease in the cell size for the dense screens the value of $s/2\pi r$ will become an argument of the same function.

Foil Materials. These include the electrically thin materials 0.01 to 0.05 mm thick. The assortment of foil materials basically includes diagmagnetic materials -- aluminum, brass and zinc. The steel foil materials are not produced by industry. The installation of foil shields is simple, for the fastening of the foil to the base of the shield is done by glue. The choice of the glue must be made considering the operating conditions of the shield which includes the temperature conditions, moisture, vibration loads, and so on.

The foil materials are basically used in the presence of a shield on the current conducting bearing structure.

The choice of the material thickness must be made considering the possibilities of the occurrence of resonance phenomena, which is illustrated by the graphs presented in Fig 1.12, where the shielding effectiveness of the material is illustrated as a function of the resonance frequency (or equivalent radius). Thus, for example, if the lowest resonance is

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expected on a frequency of 100 megahertz and it is necessary to insure shielding effectiveness of no less than 40 decibels, a thickness of a material made of aluminum or copper must be no less than 0.03 mm, and from zinc or brass, no less than 0.06 mm.

The calculation of the shielding effectiveness by foil materials is made by the formula for electrically thin materials (1.34). The effectiveness of these materials is quite high for electromagnetic field shielding and the electrical component. The magnetic component is attenuated comparatively little by these materials, and the less, the greater the wave length.

Current Conducting Paints. The use of current conducting paints for electromagnetic shielding is a highly prospective area, for their application excludes the necessity for performing complex, tedious operations with respect to installation of the shielding, the joining of its sheets and elements together. Using the current conducting paints, a shield for any purpose and on any base can be quickly made even under protection conditions. The effectiveness of the shielding of no less than 30 decibels can be obtained here in a wide frequency band.

The current conducting paints are created on the basis of a dielectric film-forming material with the addition to it of conducting components, plasticizer and hardener. As the current conducting pigments, colloidal silver, graphite, carbon black, metal oxide, powdered copper and aluminum are used. The conductivity of the coating depends on their thickness, the properties and the concentration of the current conducting pigment, the properties of the film-forming material and other factors. The current conducting paint usually is stable and retains its initial properties under the conditions of sharp climatic changes and mechanical loads.

The studies of the current conducting paints [25] demonstrate that it is inexpedient to use powdered metal as current conducting pigments as a result of oxidation of it on mixing with film-forming materials and solvent. The best results with the least expenditures, simplicity of the process of manufacturing the paint and methods of applying them to the surface come from using acetylene black or graphite as the current-conducting pigment.

An effective current-conducting paint is made up, for example, of a 9-32 lacquer (TU MKhP-3219-52) and 300% KTB pencil graphite (All-Union State Standard 4404-58). This type of paint has a surface resistance of approximately 7...7.5 ohms with a coating thickness of $(1.5...1,7)\cdot10^{-4}$ m and 5-6 ohms with a coating thickness of $(2-2.1)\cdot10^{-4}$ meters, it has good adhesion to metal, wood, textolite, plywood and plaster surfaces.

The shielding effectiveness using current-conducting paints in the logarithmic expression is defined just as for the electrically thin materials, by the formula (1.36)

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$$\underset{(1)}{\Theta_{кр}} = 20 \lg \frac{60\pi}{R_{\square}} + 20 \lg 0{,}21 \frac{\lambda}{R_э}, \qquad (2.4)$$

Key: 1. cr

where in accordance with (1.38) the term 20 lg0.21(λ/R_{shield}) is the increment $\Theta_{additional}$ of the effective shielding by the electrical components in a spherical shield for $\lambda >> 2\pi R_{shield}$. If we substitute the value of $R_{\square}$=6 ohms, in formula (2.4), we obtain

$$\underset{(1)}{\Theta_{кр}} = 30 + 20 \lg 0{,}21 (\lambda/R_э).$$
$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (2)$$

Key: 1. critical; 2. shield

While the wave length is greater than the equivalent radius R_{shield} of the shield, the effectiveness of the shielding is appreciably greater than 30 decibels. The effectiveness of 30 decibels is achieved for $\lambda/R_{shield} \sim 5$. Then as the frequency increases, the effectiveness must decrease. However, the measurements show that in this case the shielding effectiveness is still maintained at a level of 30 decibels, and for λ=10 cm, even some increase in it is observed. It is obvious that the absorption of the electromagnetic oscillations in the body of the paint layer is felt on such short waves.

The metal plating of the surfaces of various materials for electromagnetic shielding is becoming more and more widespread as a result of the high output capacity and universalness of the methods of applying coatings. Among the existing methods of applying coatings the most convenient is the spraying method. The application of the metal to a backing is realized by atomization of the molten metal by a compressed air jet. The chemical composition of the coating differs from the initial material, and the microstructure of the coating is made up of layers of different size metal particles and oxide films. In the process of formation of the coating, the sprayed metal particles strike with high speed against the surface of the substrate and are deformed. The oxide film is formed, the properties of which depend on the flight time of the particles and the activity of the metal. From the impact of the new particles the film is broken and forced outward, and the metal particles come into direct contact, insuring a strong bond with the substrate and continuous conductivity of the coating.

It is possible to apply the metal layer to any strong surface of such materials as heavy paper, cardboard, fabric, wood, textolite, plastic, dry plaster, cement surfaces, and so on. The surface of these materials must be roughed up for better adhesion, which is achieved by sandblasting. The paper, cardboard and fabric do not require this type of preparation. The applied metal layer is held tightly within the limits of the mechanical loads and deformations under which the backing is not destroyed. For example, on crushing fabrics, the metal layer is not destroyed, but breaking of metal-plated paper can lead to destruction of the coating layer.

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The metal layers can be of different thickness. The thickness of the layer does not depend on the type of metal coating, but is determined by the properties of the backing. The amount of the applied layer of metal must correspond to the physical-chemical properties of the backing material, its strength and deformation characteristics. For dense paper the metal layer must be no more than 0.28 kg/m^2; for fabric, to 0.3 kg/m^2. For a rigid backing, the amount of applied metal is not essentially limited; more significant restrictions are caused by the weight and size characteristics of the shield.

The most widespread coating is zinc. It is technological, it insures comparatively high shielding effectiveness and sufficiently mechanical strength for many shields. Just as high effectiveness can be obtained on plating dry plaster, plastic, wood and other analogous materials with zinc.

The average shielding effectiveness of the plating of the surface with zinc can be determined with an error of no more than ± 10 decibels by the empirical formula

$$\underset{(1)}{\Theta_{\text{мет}}} = 97 + 5 \lg d_0 - 20 \lg f, \qquad (2.5)$$

Key: 1. metal

where d_0 is the amount of sprayed metal, kg/m^2; f is the frequency, megahertz.

Here the mean square deviation from the mean value is no more than 3 decibels.

It is necessary to consider that expression (2.5) essentially determines the effectiveness of a real shield, for on execution of it by metal plating, sufficient seal is insured. For example, in order to insure a coating thickness of 0.1 mm, it is necessary to use about 0.8 kg/m^2 of zinc, which on a frequency of 10 megahertz gives shielding effectiveness of more than 100 decibels.

The shielding effectiveness using aluminum coatings is approximately 20 decibels higher than zinc.

In the general case, under other equal conditions the effect of the shielding using a metal layer is lower than a solid sheet of the same thickness. This is explained by the difference of the chemical composition of the coating from the structure of the initial metal, as a result of which the conductivity of the coating usually is below the conductivity of the metal itself.

With the manual method of metal plating and low metal consumption (to 0,12 kg/m^2 and less), the coating thickness turns out to be nonuniform, individual sections of the surface remain almost completely transparent,

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which leads to a sharp decrease in the overall effectiveness and almost excludes shielding of the magnetic component of the field. The effectiveness can be increased to 100 decibels or more if we increase the metal consumption to 0.6-0.8 kg/m^2 and we apply it directly to the prepared strong base.

The metal plating of the surfaces can be used successively to shield the facilities and the enclosure under the conditions of dividing the radio-electronic equipment into individual shielded compartments with non-metallic overall supporting structure, for individual devices installed in plastic housings and many other cases. Contacts for grounding and connecting other circuits can be soldered to the metal plated surfaces.

Glass with Current-Conducting Coating. This type of glass should insure the required shielding effectiveness if the optical characteristics of it do not become worse than the established limiting values. The electrical and optical properties of glass with a current-conducting coating depend on the nature of the oxides making up the conducting film, the conditions and methods of applying it and the properties of the glass itself [26]. Films made of oxides of one metal or a mixture of metals can be used for shielding. Under the conditions of maintaining the transparency of the glass with losses of no more than 20% and insuring sufficient electrical conductivity, the film thickness of the coating can fluctuate within broad limits: from $0.5 \cdot 10^{-8}$ to $(2 \cdot 3) \cdot 10^{-6}$ meters (from 5 to 2000 to 3000 nm).

Films made of tin oxide have become the most widespread, for they insure the greatest mechanical strength, they are chemically stable and they are tightly joined to the glass backing.

Glass with current-conducting coating is basically used in inspection holds and the scales of the radio-electronic equipment, in the shielded chambers to allow light to enter them. A closed glass shield with current-conducting coating is used when it is necessary to observe the processes going on behind the shield.

At the present time there is a nomenclature for glass with current-conducting coatings having a surface impedance of no less than 6 ohms with transparency becoming no more than 20% worse. The shielding effectiveness for such glass is approximately 30 decibels in the radio engineering wave band. The surface impedance depends on the thickness of the current-conducting film. The film thickness in turn determines the amount of transparency loss. Therefore when making and using glass with a current-conducting surface it is necessary to determine the optimal thickness of the film. From (1.34) it follows that the coating thickness must be

$$d = 0{,}053 \rho \Theta_0,$$

where ρ is the specific resistance of the film material, ohms-meters; Θ_0 is the shielding effectiveness in relative units; d is the coating thickness, meters.

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However, from the last expression it is impossible to find the thickness of the thin film directly inasmuch as the value of ρ determined from the tables decreases nonlinearly with the thickness d, and the relation between d and ρ itself is not known precisely. For each type of material it can be established experimentally. Thus, for example, as a result of processing the experimental data for aluminum thicknesses to $6 \cdot 10^{-8}$ m (60 nm) the approximate formula was obtained

$$R_{\square} \approx \exp (9{,}5 - 4{,}7 \cdot 10^{8} d),$$

where $R_{\square}$ is the surface impedance, ohms; d is the thickness of the film, meters.

The error in calculating $R_{\square}$ by this formula does not exceed 20%. Since glass with effectiveness below 20 decibels has no practical application, in accordance with (2.4) for shielding in the frequency band to 10 gigahertz it is necessary to obtain a surface resistance of no less than 19 ohms; therefore the thickness of the coating must be greater than or equal to

$$d \geqslant \frac{4{,}1 - \lg R_{\square}}{2 \cdot 10^{8}} \approx \frac{4{,}1 - 2{,}8}{2 \cdot 10^{8}} \approx 0{,}65 \cdot 10^{-8} \text{ м } (6{,}5 \text{ nm}).$$

As the studies have demonstrated, the effectiveness of 20 decibels for the investigated case can be obtained only with insignificant transient resistance between the film surface and the shield, which is possible with corresponding insurance of reliable and careful joining of the glass to the frame.

As the contact improves, the shielding effectiveness approaches the calculated value. The obtaining of a reliable contact with respect to the entire perimeter of the current-conducting layer of glass with the shield presents a difficult technical problem. The presence of an insufficiently tight contact alone can explain the decrease in the shielding effectiveness below 20 decibels in the 60-400 megahertz band.

The region of application of the metal plated glass for shielding purposes can be expanded when solving the problem of insuring a reliable contact between the glass surface and the shield at least as a result of a decrease in the surface resistance on the edges of the glass, at the points of contact with the shield, which can be achieved by increasing the thickness of the current-conducting film.

Special Fabrics. There are several types of special fabrics (type RT and No 4381) with metal thread that reflect electromagnetic waves. The RT fabric is made of capron thread twisted with flattened, silver-coated copper wire 35 to 50 microns in diameter.

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In the number 4381 fabric the thread is interwoven with enameled microwire PEL-0.06 (All-Union State Standard 2773). The number of metal threads can be 30x30, 20x20, 10x10 and 6x6 per cm^2. Inasmuch as the wire is insulated, the surface resistance of this fabric is high. In the mesh of the fabric there is no electrical contact. It is designed for protection against microwave oscillations. Usually special suits for individual biological shielding are made from this fabric. A detailed study is made of the mechanism, shielding effectiveness and structure of the individual shielding against electromagnetic fields in [26, 27].

Radio Absorbing Materials (RPM). The radio-absorbing materials do not belong to the shielding materials, although some of them are produced on a metal base which with careful connection of its individual parts and elements can serve as a shield. Joining sheets of metal introduced into the absorbing layer, a soft screen or foil presents definite technological difficulties, and the effectiveness of the shielding by the base of such RPM fabric will be insignificant. Therefore the shield usually is covered with absorbing material with the basic purpose of decreasing the radio wave reflections inside it. The presence of significant absorptions of electromagnetic energy to a significant degree eliminates the occurrence of a diffuse field, it attenuates the reaction of the shield to the shielded elements, and it facilitates the insurance of biological shielding.

The measurement of the radiation patterns of antennas, the study of the reflecting properties of various bodies, climatic and other tests of radio technical equipment providing for strict regulation of the external condition (for example, moisture, temperature, and so on) cannot be carried out in the test areas. In the shops and laboratories these tests and measurements must be performed in facilities which simulate "free" space with constant parameters. In such facilities, giving them a special shape and using radio-absorbing materials, it is possible to create a space in which the diffuse field will be 300 to 1000 times attenuated, that is, in practice only the incident wave field will exist which will permit sufficiently exact measurements to be taken.

If it does not appear possible to realize the structure of an air duct for the cooling system of radio-electronic equipment operating in microwave range by the principle of the limiting wave guide with comparatively large cross section, this problem can be solved by creating an air duct of the "elbow" type with coating of its inside surface with RPM.

The presented examples of the modern application of RPM indicate how wide and varied it is.

For the selection of the corresponding radio-absorbing material it is necessary to give the operating frequency band in which radio wave absorption must take place, the operating temperature range, the magnitude

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of the admissible reflection coefficient, the type of base and the material itself (rigid, elastic, assuming the required shape, and so on).

The spatial absorbing materials have a reflection coefficient of 1 to 3%. The absorption characteristics become worse as the angles of incidence of the electromagnetic waves increase. There are narrow-band materials of the interference or resonance type, the range of which (for example, KhV type) is approximately $\lambda \pm 15\%$, and wide-band materials.

The narrow-band materials are a layer of material itself with losses fastened to a metal base. The layer thickness $d \approx \lambda_M/4$, where λ_M is the wave length in the material, more precisely, $d=\lambda_M/4\sqrt{\varepsilon_r \mu_r}$ where ε_r, μ_r are the relative dielectric permeability and the relative magnetic permeability of the coating respectively. The field absorption of such materials is basically obtained as a result of interference and mutual compensation on the surface of the radio-absorbing material of two waves which are reflected from the surface of the absorber and from the surface of the metal base (shield) respectively. The oppositeness of the phase and equality of amplitudes of these waves are achieved by selecting the absorber parameters. A significant deficiency of such RPM is their narrow-band nature. The expansion of band within the limits of the single-layer structure is impossible. However, they have a rare advantage for radio-absorbing materials, such as small thickness (especially for materials in the centimeter and higher-frequency bands).

As a rule, the wide-band radio-absorbing materials are sheets of uniform absorbing material with surface relief in the form of projections (spines) of pure metal or conical shape. The wide band radio-absorbing materials can be formed also from flat sheets of multilayer absorbing material. The operating principle of such materials is based on the gradual attenuation of the electromagnetic energy of the incident waves in the body of the material and conversion of it to thermal energy as a result of inducing scattered weak currents, magnetic hysteresis losses or high-frequency electrical losses. The wide-band materials operate on all frequencies exceeding some limit determined by the thickness of the material and its average dielectric constant. With a decrease in frequency the required thickness of the absorbing material increases, and at frequencies of 100-120 megahertz pure metal blocks are already used up to 500 mm high on bases up to 200x200 mm^2 square or flat coatings to 350 mm thick.

The limiting radiation energy which can be absorbed by such material depends on its maximum operating temperature.

The radio-absorbing materials are made in the form of thin rubber rugs, flexible or rigid sheets of poralon or wooden fiber impregnated with the corresponding compounds. There are radio-absorbing materials in the form of thin ferrite plates. The materials can be installed by glueing or fastening the shielding to the base by special fasteners.

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The simplest absorbers of microwave energy are paints which have low reflection coefficients. Thus, for example, the NTS00-003 type paint in the wave length range of has a reflection coefficient with respect to power to 50%. The graphited No 369-61 textolite has the same parameters. At the present time both Soviet and foreign industry are producing a broad nomenclature of RPM. Classified and generalized information is presented in Table 2.1 on the characteristics of certain Soviet-produced RPM [28], and Table 2.2 [29] contains analogous data on the RPM produced abroad.

Electrically Conducting Glue (EPK). The filling of epoxy resin with finely-disperse powdered metal (iron, cobalt, nickel and so on) has made it possible to obtain electrically conducting glue which has a tearing strength of up to 50 MPa (500 kg/cm^2) with a specific electrical conductivity to 10^{-6} (ohm-m)$^{-1}$, resistant not only to moisture, but also to various aggressive media and providing insignificant shrinkage after hardening. The hardening time can be brought to 5 minutes if this process is carried out using high-frequency current [30].

Along with the application of the electrically conducting glue instead of solder, bolts, and so on, it appears expedient to use it also in electromagnetic shielding. The joining, fastening of contact systems and various shielding elements, filling the slits and small openings, installation of the shield on the bearing structure -- these and other operations can be successfully accomplished using electrically conducting glue with high shielding effectiveness and a reduction in the volume of installation operations.

By varying the consistency of the electrically conducting glue to the paint consistency and retaining a surface resistance of even up to 0.1 ohms per unit area, it is possible to obtain, as is obvious from (1.36), a shielding effectiveness of 60 to 65 decibels, approaching the effectiveness of metal.

2.3. Contact Structures of Electromagnetic Shielding. Contact Joints and Shielding Effectiveness

The actual shields which consist of a large number of elements joined together cannot be considered as uniform. It is necessary to consider phenomena caused by nonuniformity of the structural elements.

At the points at which the sheets are joined and the connections of the elements, the current passes through sections with sharply diminished cross section inasmuch as a reliable contact is realized not over the entire contact surface, but only at individual points or in individual areas. This leads to local increases in current density and nonuniform distribution of the currents, to an increase in the shield resistance and a reduction of its effectiveness as a whole.

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Table 2.1

Parameters of Some Soviet-Made Radio-Absorbing Materials

(1) Марка материала	(2) Характеристика основы и параметры материала												
	(3) Ферритовые поглощающие пластины	(4) На основе древесного волокна	(5) Резиновые коврики	(6) На основе поралона	(7) Шиповидная поверхность	(8) Магнитоэлектрические пластины	(9) Широкий интервал рабочих температур	(10) Работающие при высокой влажности окружающей среды	(11) Диапазон рабочих волн, см	(12) Отраженная мощность, %	(13) Размер пластин, м·10⁻³	(14) Масса 1 м² материала, кг	(15) Толщина материала, мм
(16) СВЧ-068	●								15...200	3	100×100	18...20	4
(17) „Луч"		●					●	●	15...150	1—3	600×1000		
(18) В2Ф2									0,8...2	2	345×345	4...5	11...14, в том числе высота шипов 8...11 (20)
(19) В2Ф3			●		●				0,8...4	4	345×345	4...5	
(21) ВКФ-1													
(22) „Болото"				●					0,8...100	1—2			
(23) ХВ-0,8 (24) ХВ-2,0 (25) ХВ-4,4 (26) ХВ-6,2 (27) ХВ-8,5 (28) ХВ-10,6						●			0,8...10,6	2	350×400	3...10	1...3

Key:

1. Type of material
2. Characteristics of the base and material parameters
3. Ferrite absorbing plates
4. Based on wooden fiber
5. Rubber rugs
6. Based on poralon
7. Spiny surface
8. Magnetoelectric plates
9. Broad operating temperature range
10. Operating with high ambient humidity
11. Operating wave band, cm
12. Reflected power, %
13. Plate size, $m \cdot 10^{-3}$
14. Mass of 1 m^2 of material, kg
15. Material thickness, mm
16. SVCh-068 (microwave-068]
17. "Luch" [Beam]
18. V2F2
19. V2F3
20. including the height of the spines 8 to 11
21. VKF-1
22. "Boloto" [Swamp]
23. KhV-0.8
24. KhV-2.0
25. KhV-4.4
26. KhV-6.2
27. KhV-8.5
28. KhV-10.6

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Table 2.2

Parameters of Radio-Absorbing Materials Produced Abroad

Марка материала (1)	(18) Характеристика основы и параметры материала															
	(2) Пенематериал, диэлектрик, не горит	(3) То же, жесткий	(4) Твердый пенематериал, водонепроницаемый, не горит	(5) Материал для покрытия полов, выдерживает нагрузку до 2 кгс/см²	(6) Твердый пенематериал пленкой из стеклопластика	(7) Керамический пенематериал, поглощает высокие уровни энергии	(8) На основе животного волоса	(9) Пеноблоки	(10) Пирамидальная поверхность	(11) Выдерживает температуру до 180°С	(12) Интервал рабочих температур —60...+650°С	(13) Диапазон длин волн, см	(14) Отраженная мощность, %	(15) Размер блоков, м	(16) Масса 1 м² материала, кг	(17) Толщина материала, мм
CV-6	●											4	0,01		4,0	152
CV-9	●											12	0,01	0,6×0,6	60	200
CV-12		●										32	0,01	0,6×0,6	80	300
CV-18		●										66	0,01	0,6×0,6	12,0	450
FR-330			●									12	1,0	0,9×0,3	2,4	50
FR-340			●									32	1,0	0,9×0,3	5,0	100
FR-350			●									66	1,0	0,9×0,3	10,0	200
FRL-330				●						●		12	2,0	1,0×0,3	3,5	50
FRL-340				●						●		32	2,0	1,0×0,3	6,0	100
FRL-350				●						●		66	2,0	1,0×0,3	10,0	200

Key:

1. Type of material
2. Foam material, dielectric, does not burn
3. The same, rigid
4. Solid foam material, waterproof, does not burn
5. Material for covering floors, withstands loads of up to 2 kg-forcec/m^2
6. Solid foam material with fiberglass film
7. Ceramic foam material, absorbs high energy levels
8. Based on animal fiber
9. Foam blocks
10. Pure metal surface
11. Withstands a temperature to 180°C
12. Operating temperature range -60 to +650°C
13. Wave length range, cm
14. Reflected power, %
15. Size of blocks, meters
16. Mass of 1 m^2 of material, kg
17. Thickness of material, mm
18. Characteristics of the base and material parameters

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Table 2.2 [Continued]

(1) Марка материала	(18) Характеристика основы и параметры материала														(16) Масса 1 м² материала, кг	(17) Толщина материала, мм
	(2) Ненаэтерная, анизотропная, не горит	(3) То же, жесткая	(4) Твердый неоматерная, водоненропницаемый, не пит	(5) Материал для покрытия полов, выдерживает нагрузку до 2 кгс/см²	(6) Твердый неоматерная плитной из стеклопластика	(7) Керамический неоматерный, потолок высокие уровни энергии	(8) На основе животного волоса	(9) Ненобложка	(10) Пропитанная поверхность	(11) Выдерживает температуру до 180°С	(12) Интервал рабочих температур —60...+650°С	(13) Диапазон длин волн, см	(14) Отражающая мощность	(15) Размер сторон, м		
CHW-590								●				100	1,0	0,6×0,6	2,7	300
CHW-580												150	1,0		3,6	450
CHW-570					●				●			300	1,0		6,8	900
CHW-560												600	1,0		9,5	1830
HT-98											●	12	1,0	0,9×0,3	10,0	38
HT-99						●						32	1,0		14,0	76
HT-101												66	1,0		20,0	152
HT-102												100	1,0		40,0	1305
CH-445							●					7	1,0		1,0	25
CH-460												12	1,0		2,5	50
CH-475												32	1,0		4,0	110
CH-490												66	1,0		7,5	200

[For key, see p 67]

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In order to explain why an increase in the overall resistance of the shield leads to a reduction of its effectiveness, it is sufficient to represent it as a volumetric resonator with distributed parameters in which the Q-factor is approximately proportional to the effectiveness ϑ_{Σ}.

Increasing the loss resistance of the resonator (shield) leads to a reduction of its effectiveness (1.41). The total active resistance of the shield $R_{0\vartheta}$ is made up of the sum of the resistance R_s of a continuous shield, the resistance R_k caused by the joint contacts and the transitional resistance R_{π} of the opening and nonopening elements, that is, $R_{0\vartheta}=R_s+R_k+R_{\pi}=R_s+R_{additional}$, where the additional loss resistance $R_{additional}=R_k+R_{\pi}$.

The resistance R_s of a continuous shield usually is very small. For example, on a frequency of f=10 megahertz in a steel shield it is a total of $2\cdot10^{-2}$ ohms.

The contact joints in the shields are distinguished with respect to structural design and executed functions from the ordinary electrical contacts. By the electrical contact usually we mean the joining of two conductors in which reliable passage of an electrical current without noticeable losses through these conductors is insured. From this point of view the functions of the ordinary contact joints and the contact joints in the shields are identical, inasmuch as for a thickness d of the shield less than the depth of penetration of the field into its structural elements, that is, $d<\delta$, the effectiveness is directly proportional to the conductivity of the shield material. The introduction of large transitional contact resistances into the shield can be represented not only as a phenomenon equivalent to worsening of the Q-factor of the resonator, but also as a phenomenon equivalent to the introduction of unmatched loads into the transmission line or into the long line leading to reduction of the electrical magnetic layers and nonuniform distribution of the eddy currents. However, the dimensions of the contact joints in the shield are large, and they frequently cut through a significant part of its surface. Therefore in the indicated representations we are not talking about the loss resistances of the point contacts, but the contact joints of large geometric dimensions where the contact areas, the state of the contact surfaces, the distribution of the contact forces, the wear resistance and other factors and the parameters have great significance. These large contact joints of the surfaces of the elements require the use of specific solutions during design as is demonstrated in §3.4.

With respect to purpose, the contact joints of the shields and their elements can be divided into four groups.

1. Unsplit Contact Joints. They are designed for permanent connection of the parts and elements of the shields. These connections usually are welded or soldered. The increase in total loss resistance as a result of such contact is highly insignificant, for here with comparatively simple and developed technology it is possible to insure parameters close to the parameters of an ideal contact.

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Three versions of electric welding of metals are theoretically possible: by heating to fusion (electric arc welding), heating until a plastic state of the metals is obtained with simultaneous mechanical compression (electric contact welding) and compression of the joined parts without heating (cold welding). The welding by any of the indicated methods finishes with elimination of the contact boundary and the formation of a single crystalline monostructure.

In the case of arc welding the weld is uniform in structure and the electrical resistance of it is no more than resistance of a section of the metal of the same length in the zone not affected by the weld.

Contact welding includes spot and butt welding. The electrical resistance at the location of this type of weld usually does not increase by comparison with the resistance of the solid metal.

A variation of welding is soldering, which includes the process of the building up of one metal on the other called tin-plating [tinning]. Tinning is carried out with preparation of the joined surfaces for soldering or the preparation of the surface for insurance of a tight unwelded joint.

Soldering of metals is possible as a result of the fact that metals in close contact are capable of dissolving in each other, diffusing in each other both in the liquid and the solid state. The solder, joining with the basic metals, bonds them mechanically and electrically, although the crystalline structure of the joint differs from the structures of the soldered materials. The choice of the solder and the clearance between the metals has great significance for the quality of a soldered joint. Since the resistance of the solder usually does not exceed the resistance of the base metals, it is possible to consider that the total resistance does not increase. Consequently, an unsplit contact realized by solid welding or soldering in practice does not change the total resistance of the shield. The quality of the welding and soldering after cleaning must be checked carefully in order to detect incompletely welded or incompletely soldered surfaces, burns and other defects.

The unsplit contact joint can be also made unwelded. For example, when using foils, the sheets are joined by single or double seams, insuring sufficient shielding effectiveness. At high frequencies even when the direct contact is disturbed and a film is formed, the transition resistance will be insignificant inasmuch as the effect of the transition capacitance in this case is sufficiently perceptible.

When realizing an unsplit contact using bolts or spot welding with defined spacing, the total resistance increases, as a result of which the shielding effectiveness decreases. This type of joining of sheets is resorted to where it is possible to be limited to comparatively low value of it.

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2. Split Contact Joints. These joints can be dismantled periodically. These include the installation of various shields, covers, partitions, installed equipment, and so on. With respect to type of joining to the shield they are considered clamped. The contact surfaces are with time subject to oxidation and conversion, the clamps become weaker, the inserts dry out, and therefore the split joints must periodically be cleaned and subjected to preventive maintenance.

3. Sliding Contact Joints. These joints are used for constant or periodic variation of the relative position of the shield elements. This type of contact joint is used primarily for rotating and moving parts of the shield. A characteristic example here is the projection of the shafts of the tuning devices and control elements of the radio-electronic equipment beyond the boundaries of the shield.

4. Contact Joints of Opening Parts of the Shield. This type of contact system is with respect to its structural design the most complicated, it requires careful execution, for it basically determines the magnitude of the additional loss resistance.

The studies indicate that for shields and complex structural design with different types of contact joints $R_{об}/R_s$ can reach 10-15, which leads respectively to worsening of the effectiveness also by approximately 10 to 15 times. However, in practice, the decrease in effectiveness can turn out to be not so large as a result of shunting of the transient contact by the inductive and capacitive components of the total resistance.

The reliable operation of electrical contacts is insured by the structural design, carefulness of manufacture, proper selection of the coatings of the materials and contact compression. For significant compression the contacts retain small transition resistances comparatively well, and for weak compressions, even coatings made of noble metals and large contact surfaces do not guarantee that this resistance will remain within the limits of the required values. However, increasing the contact pressure creates defined difficulties for dismemberment of the contact. Thus, the choice of the structural design of the contact devices for the opening elements of the shield must be made under the conditions of contradictory requirements. On the one hand, it is necessary to insure simple, easy dismantling of the contact, for example, for the opening doors of the shield,and on the other hand, it is necessary to obtain great operating reliability of the contact system with comparatively small transition resistances. The generalization of references [31-37] and the experimental studies have made it possible to establish a relation between the form of the contact surfaces, the value of the transient resistances and the contact compression on variation of it. Within limited bounds, this function is represented graphically in Fig 2.1. The contact systems for electromagnetic shielding purposes are most expediently made of phosphorous bronze and brass. The least transition resistance is insured by the contacts of circular and pyramidal shape. On compression, for example, with a force of 1 kg-force, the transition resistance will be 10^{-4} ohms. In the shielding of the

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radio-electronic equipment, as a rule, there are opening parts in the form of doors, windows, covers, and so on, depending on how frequently access to the elements located inside the equipment or an equipment module is necessary. The structure of these shield joints is the most labor-consuming, primarily as a result of the necessity for insuring a tight metal contact between the frames and jambs of the doors, windows, covers, and so on.

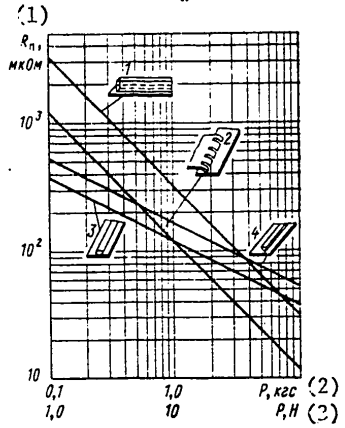

Figure 2.1. Dependence of the transition resistance on the contact compression:
1 -- for flat contact surfaces; 2 -- for a flat surface with brush contact; 3 -- for a flat surface with cylindrical contact; 4 -- for a flat surface with pyramidal contact

Key:
1. $R_п$, microohms
2. P, kg-force
3. P, newtons

The contact devices used for this purpose can be regulatable or nonregulatable (constant dimensions).

The regulatable contact is used for comparatively large door openings where it is necessary to insure uniform contact pressure over the entire perimeter. Double contacts can be used for great reliability. The contact devices can be located both on the end of the door and in the jamb itself. The basic requirements which are imposed on the contact devices reduce to insuring a tight contact around the entire perimeter, reliability and the possibility of easy opening and closing of the doors. The latter requirement is especially important in cases where the doors are frequently opened, for example, for the shielded facilities of enclosures, and so on. Under these conditions it is preferable to have contact devices on the door jamb, but then special stops are locks are required to keep the doors in this position in which sufficient pressure will be exercised against the contacts. The best result is achieved when the compression of the electrodes of the contact is under the effect of the mechanical reaction of a deformed spring or the reaction of a deformed spring placed under the contact.

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Table 2.3.

Contact Systems for Opening, Rotating and Removal Structures of Electromagnetic Shields

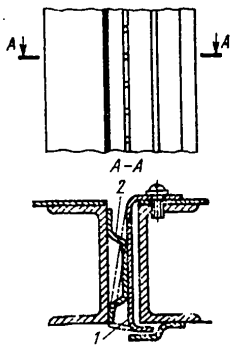
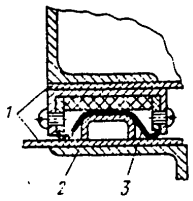
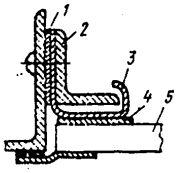
Sketch	Brief characteristics
	Spring contact. Pressure is applied to the contact as a result of deformation of a spring 1 on making contact with the cleat 2. It is used to insure contact of opening elements (for example, doors) of the shields for radio transmitters and other radio technical devices. It is simple to manufacture and convenient to operate and maintain. The effectiveness of the shielding is 60 to 70 decibels.
	Contact with rubber backing. Pressure is applied to the contacts under the effect of the reaction of a deformed backing (rubber) on the metal contact surfaces. The contact spring 3 when pushed against the contact bar 2 insures reliable contact between the frame of the shield 1 and the shield of the opening device.
	Spring contact. The contacts are put under pressure as a result of deformation of the contact spring 3 on making contact with the door 5, around the perimeter of which a contact strip 4 has been fastened. Around the perimeter of the opening formed by the opening part of the shield, a copper tape 1 and a contact spring 3 have been fastened using an angle iron 2.

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Table 2.3 [continued]

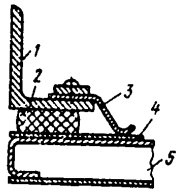
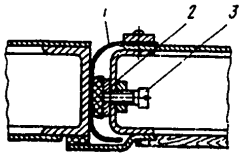
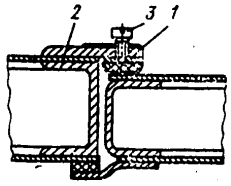
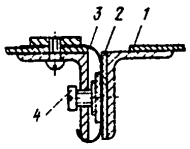
Sketch	Brief characteristics
	Spring contact. Pressure is applied to the contacts as a result of the reaction of the rubber seal 2 and deformation of the contact spring 3. The contact strip 4 is attached to the door jamb 5. An angle iron 1 is welded to the opening of the shield, to which the spring 3 and the rubber seal 2 are attached. In order to maintain contact, a clamp must be installed on the door.
	Contact system not requiring a clamp on the door. A contact spring 1 is installed on the shield of the door around the perimeter. The pressure of the spring is regulated by the clamping device 2 and a screw 3. The uniform clamping of the contact spring insures maintenance of shielding effectiveness at a level of 80 decibels.
	The same. Regulation of the compression of the contact spring in another plane is provided, and a device is required for clamping the door. The contact spring 1 is fastened to the door frame 2. Uniform pressure is applied to the spring by the screw 3.
	The same, but simplified design.

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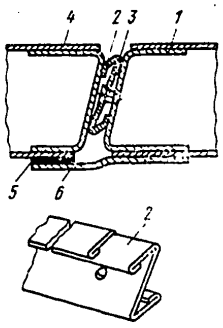
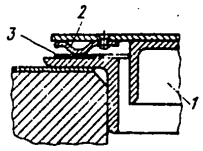
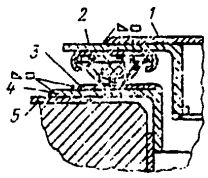
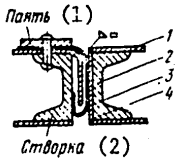
Table 2.3 [continued]

Sketch	Brief characteristics
	Contact device with "floating" contact spring: 1 -- opening door: 2 -- "floating" contact spring made of beryllium bronze: 3 -- special fastening screw; 4 -- frame of the door opening; 5 -- rubber shock absorbing insert; 6 -- bounding supporting cleat. The contact system is reliable in operation, it is self-cleaning, it insures a reliable contact for a long period of time, and the shielding effectiveness is up to 80 decibels.
	Single-contact spring. System 2 is located on the door jamb 1. The contact strip 3 is fastened to the frame of the door frame. It requires the presence of a clamping device for the door.
	The same with the application of a seal: 1 -- shield of the door jamb; 2 -- rubber cord tightened by a copper screen soldered to the door frame; 3 -- contact strip (brass); 4 -- shield; 5 -- frame of the door box.
	End-type single contact device; 1 -- shield; 2 -- frame; 3 -- spring; 4 -- contact strip.

Key: 1. solder; 2. door

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Table 2.3 [continued]

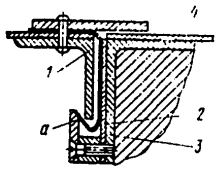
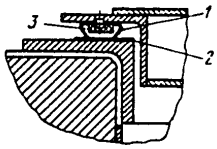
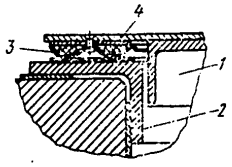
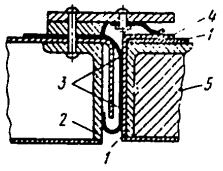
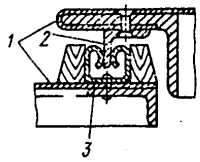
Sketch	Brief characteristics
	End-type, single-contact device with additional contact at point a: 1 -- door frame; 2 -- contact spring; 3 -- box frame. Used for shielded chambers.
	Contact system located on the door jamb. The contact is self-sharpening, it requires the application of a lock (clamp) for the door. When the door closes the spring 1 makes contact with the cleat 2 in two planes. The shock absorbing cord 3 promotes improvement of the contact.
	Double contact located on the door jamb: 1 -- door; 2 -- door box frame; 3 -- contact spring; 4 -- rubber cord. Requires installation of a lock on the door. Insures easy opening of the doors.
	Combined double contact. The contacts are located both on the end of the door and on the jamb, which permits elimination of the lock: 1 -- shield; 2 -- door jamb; 3 -- contact spring; 4 -- contact cleat; 5 -- door frame.
	Knife type contact. The contact spring 3 is bonded to the shield 1. The contact knife 2 is fastened to the shield 1.

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Table 2.3 [continued]

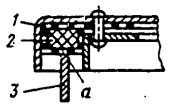
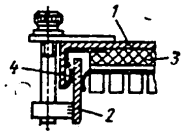
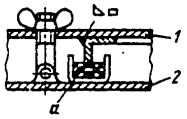
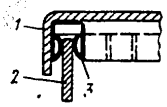
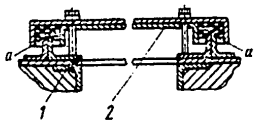
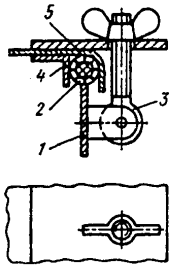
Sketch	Brief characteristics
	Contact of a removable cover with the shield housing is insured at point a. The contact surface of the shield 3 must be clean. The rubber insert 2 is installed in a brass screen 1.
	Contact of a removable cover with a shield is insured by a knife-type device with a bolt used as the lock: 1 -- removable cover; 2 -- shield; 3 -- insulating insert; 4 -- contact spring
	Contact of a removable cover 1 with the shield is insured for contact of the angle iron with the brass screen at point a. Compression is provided by a bolt fastened to the housing 2.
	Knife-type contact. The spring 3 made of bronze (strip, slit) is fastened to the cover 1; the contact knife is the housing 2.
	Compression of the contact surfaces of the point a is realized using screws which pull the cover 2 against the shield 1.
	Contact used for frequently opened covers. Tight contact between the shield 1 and the cover 4 is created using a clamping screw 3. The copper mat 5 in which the cord 2 has tight contact with the cover.

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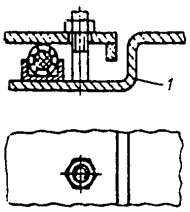
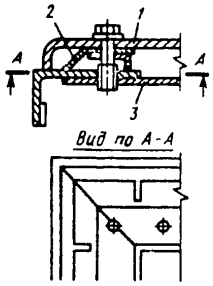
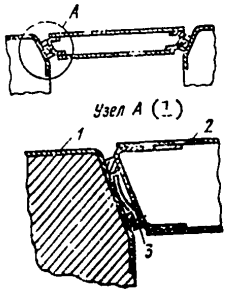
Table 2.3 [continued]

Sketch	Brief characteristics
	Approximately the same. The shock absorbing cord 1 is in the copper mat which has a reliable electrical contact with the housing. The clean surface of the cover has direct contact with the copper mat.
	The contact is insured by contact of the contact spring 2 fastened to the cover 1 with the contact cleat of the frame 3.
	When it is necessary to insure access to equipment under the floor of the shield, special covers are used (2) which can under their own weight insure required contact with the shield (1) (3 -- contact spring).

Key: 1. Assembly A

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Table 2.3 [continued]

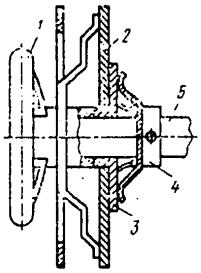
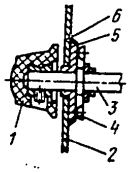
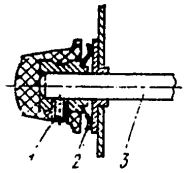
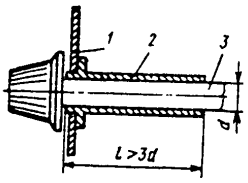
Sketch	Brief characteristics
	Projection of the metal shaft of the handle (tuner) of a powerful stage. The contact device is made in the form of contact brushes and a sleeve fitted on the metal shaft from the inside which make contact with the surface of the shield: 1 -- wheel (knob); 2 -- panel; 3 -- bushing; 4 -- sleeve; 5 -- shaft.
	Projection of the metal shaft of the tuning knob insuring brush contact with the inside of the shield: 1 -- control knob; 2 -- shield; 3 -- metal shaft; 4 -- contact ring; 5 -- brass bushing; 6 -- welded joint.
	Projection of the metal shaft of the tuning knob with insurance of brush contact with the outside of the shield: 1 -- stop screw; 2 -- contact spring; 3 -- shaft.
	Projection of the nonmetallic control knob shaft. The latter passes through a metal connecting pipe 2. The dimensions of the connecting pipe are determined by the data in Table 2.6 (1 -- shield; 3 - shaft).

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Table 2.3 [continued]

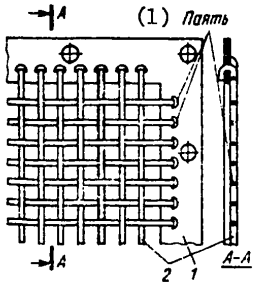
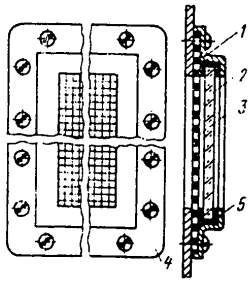
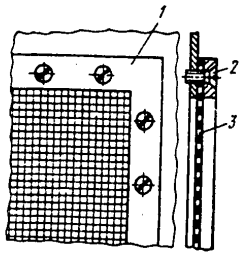
Sketch	Brief characteristics
	Shielding of the inspection openings with fitting of a screen 2. This type of shielding is used when a screen with 5x5 mm mesh or more is used with a wire diameter of 0.5 to 0.7 mm. Each wire of the screen is soldered using POS-40 solder. The frame 1 is copper or brass. It is fastened to the screen by screws. The point of contact of the frame with the shield must be tinned or zinc-plated.
Key: 1. solder	
	Shielding of glazed inspection openings by metal screen 3 using the framing 1. Between the glass 2 and the framing a rubber insert 5 is laid. The points of contact of the screen with the housing or the panel 4 must be covered with tin.
	Shielding of the inspection openings by applying screens without protective glass. The screen 3 is laid on the cleaned panel and is fastened by the frame 1 using the screw 2.

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Table 2.3 [continued]

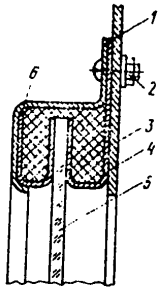
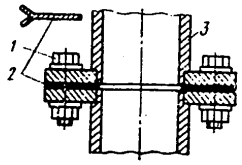
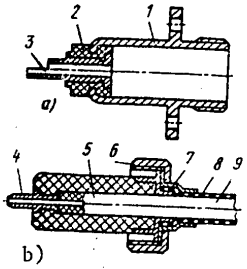
Sketch	Brief characteristics
	Shielding of the inspection openings by using glass 5 with current-conducting surfaces. In order to improve the surface contact between the glass and the shield 3, a rubber packing 4 is used which is wrapped in a contact insert made of tin foil 6. The points of contact of the clamp 1 with the insert 6 in the shield must be tin-plated. The structure is drawn together by the screw 2.
	Flanged wave connection. The joining of the wave guides 3 is realized by using the clamping bolts 1 and the contact insert 2 made of beryllium bronze. The application of the spring insert with slit lobes bent in different directions insures a shielding effectiveness to 80 decibels.
	Single-contact shielding plug. The shielding socket (a) is installed on the housing (shield) of the instrument and is made up of the plug housing 1, the insulating bushing 2 and the contact socket 3. The single-contact plug (b) is made up of the male plug 4, the insulator 5, the nut 6 for joining with the shielding socket, the bushing 7 for insuring contact with the shielding mat of flexible wire 9. The shielding socket is made in accordance with the limiting wave guide principle.

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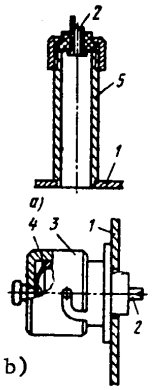
Table 2.3 [continued]

Sketch	Brief characteristics
	Shielding of control measuring sockets: a -- using limiting wave guide, b -- with the application of a blind flange; 1 -- shield; 2 -- contact socket; 3 -- blind flange; 4 -- contact insert; 5 -- connecting pipe.

The structural designs of contact systems for opening doors, covers, hatches, inspection opening, control shafts, and so on are schematically illustrated in Table 2.3. The systems must be made so as to exclude the formation of slits between the shield housing and the opening element.

A quality characteristic of the contact system is its electric seal which can be expressed quantitatively in terms of the shielding effectiveness.

The contact devices in Table 2.3 insure shielding effectiveness to 80 decibels in a wide frequency range (0.15 to 1000 megahertz), and the double contact systems with regulation of the contact pressure, to 100 decibels. The experimental testing of the shields with multiple use of the indicated contact systems demonstrated the reliable operation of them [38].

The quality of the contact becomes worse with time as a result of aging. Therefore the contact device requires periodic inspection and preventive maintenance (cleaning of the surfaces, regulation of the contact pressure, and so on).

The presented contact systems can be used in shields of any type, but in each specific case of application it is necessary to begin with the purpose of the shield, its dimensions, location and other factors.

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2.4. Ways of Joining the Sheets of the Skin of the Shields

In order to insure an electric seal, the sheets of the shield must be joined appropriately.

It is recommended [38] that the following types of joints be used: dovetail (with overlap), butt and with single or double seams.

Several versions of the joining of metal sheets by a solid, continuous dovetail seam on a frame of angle or bar iron and without a frame are illustrated schematically in Fig 2.2. The overlap of one sheet by the other must be 20 to 50 mm. The dovetail joining of the sheets insures high shielding effectiveness, it is technologically the simplest, and it can be realized both with respect to the frame of the shield and without the frame.

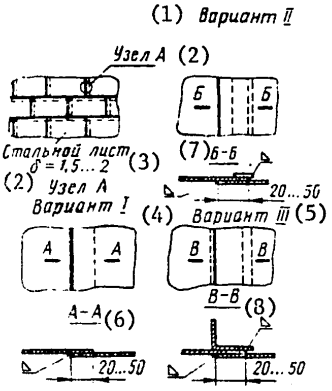

Figure 2.2. Dovetail joining of the sheets of a shield
Key:
1. Version II
2. Assembly A
3. Steel sheet δ=1.5 to 2
4. Version I
5. Version III
6. Section A-A
7. Section B-B
8. Section C-C

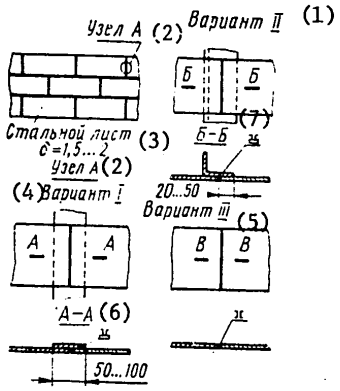

Figure 2.3. Butt joining of the sheets of a shield
Key:
1. Version II
2. Assembly A
3. Steel sheet δ=1.5 to 2
4. Version I
5. Version III
6. Section A-A
7. Section B-B

However, this type of joint requires additional finishing of the surfaces of the shield in order to lend them the necessary external appearance. It leads to a defined increase in metal consumption and weight of the shield.

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This joining is used predominantly to shield facilities and enclosures, the inside surface of which is faced further. In the case of direct shielding of the equipment and elements of it, the dovetail joining is used when the shield does not have a frame. Among the versions presented in Fig 2.2 the most widespread is the first.

If welding or soldering is carried out with respect to the frame, then butt joining of the sheets of the shield skin is more convenient (see Fig 2.3). Here the required overlap is created by the frame or angles. The butt joining with respect to the frame insures that smooth surfaces will be obtained. After finishing the welding or soldering point and painting the shield, it takes on the appropriate external appearance. This form of joining insures high shielding effectiveness, but it is less technological than dovetail joining.

Version I of joining (Fig 2.3) is used for shielded facilities and enclosures, and Version II, for equipment.

The structural design of the frame is determined by the purpose of the shield, the location of the interna devices and the size of the metal sheets. Usually the frame is made of angle or bar steel. Wooden frames are used to fasten screen materials.

The butt joining of the sheets without the frame (Version III, Fig 2.3) is used for small screens and miniature elements of the radio-electronic equipment with subsequent thickness of the shield material.

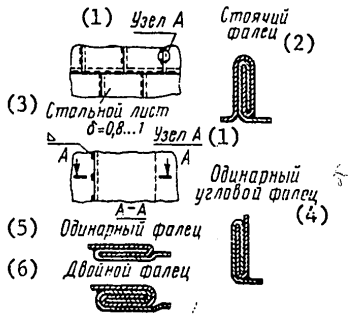

Figure 2.4. Joining of the sheets of the screen by crimped shields

Key:
1. Assembly A
2. Standing crimp
3. Steel sheet
4. Signal angle crimp
5. Single crimp
6. Double crimp

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Fig 2.4 illustrates the possible methods of joining tin plate sheets and galvanized steel by crimping. In order to obtain rigid and stable contact of the joined surfaces, single and double crimps at the points indicated in the figure are soldered along the entire length of the shield.

The above-investigated contact devices resulting from welding or soldering have negligibly small transition resistance. However, in cases where the application of welding or soldering turns out to be impossible or inexpedient, the contact is not continuous, and does not appear possible to neglect the transition resistance. In order to discover the mechanism of the effect of the transition resistances of the contact system on the shielding effectiveness under these conditions, let us consider the overall equivalent diagram of the electric contact.

In the general case, without considering the surface resistances of the contact surfaces, the equivalent circuit of the electric contact can be represented as illustrated in Fig 2.5, a.

The active resistance $R_п$ expresses the properties of the complete, tight contact of the joined surfaces. Sometimes it is called the basic transition resistance. The elective component of the electric contact turns out to be series joined to $R_п$, and it represents the inductiveness of the direct wire of arbitrary thickness, the length of which is equal to the mean diameter of the apparent complex surface.

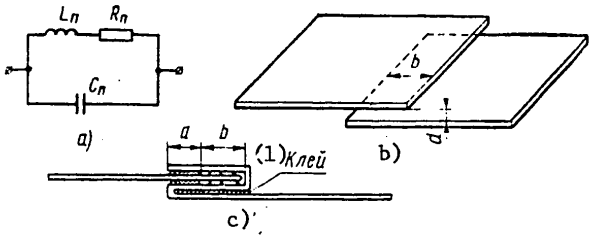

Figure 2.5. Joining of electrically thin shield materials

Key:
1. Glue

As applied to the structural designs of the shields of radio-electronic equipment, shielded facilities and enclosures, the resistance of this inductance is almost always negligibly small in a very broad frequency band.

The capacitance $C_п$ included parallel to the branch with active resistance $R_п$ expresses the properties of the part of the contact where there is no complete contact of the contact surfaces. As is known, the contact surfaces are rough, and the complete contact occurs only in individual

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regions of the surfaces. Between the other regions where there is no complete contact, sections are formed with comparatively high local capacitances. This is promoted by the formation of oxide or salt films having insulating properties on metals not having sufficiently tight contact.

The capacitance C_{π} and the inductance L_{π} form the reactive resistances of the transition zone. In well-executed contact systems with comparatively large contact pressures and clean contact surfaces, it is possible not to consider the reactive components of the total contact resistance. However, at high frequencies representing a significant part of the operating bands of many shields, the reactive component of the transition resistance can turn out to have a significant effect on the operation of the contact system. In this case the most perceptible is the effect of the resistance of the transition capacitance C_{π}.

The experimental studies and calculations, for example, indicate that the transition capacitance of the pure contact pair of metals with the apparent contact area of 5 mm^2 coated with dielectric film 20 mm thick is approximately 200 picofarads. The resistance of this capacitance on a frequency of 10^8 hertz is 8 to 9 ohms. If the basic transition resistance of the contact is tens and hundreds of times less than this amount, which occurs in practice, then it is possible not to consider the indicated capacitance. However, conditions are possible under which the capacitive component of the parallel transition resistance turns out to be less than or commensurate with the active component. Most frequently such conditions occur on frequencies above $2 \cdot 10^8$ hertz.

Fig 2.5, b shows the dovetail joining of the shield sheets in which a surface transition resistance of the overlap characterizing the electric seal of the contact is created in a region of length b.

If we consider the two surfaces of unit area applied to each other, one of which is a uniform foil, and the other a contact surface, then it is obvious that their resistances turn out to be included in series and, inasmuch as the resistance of the first surface is appreciably less than the second, the total resistance will be determined by the transition resistance of the contact.

Numerous measurements in the frequency band above 200 megahertz demonstrated that the mean value of the surface transition capacitive resistance of the contact as a result of approximation with an error of no more than $\pm 15\%$ can be represented by the function

$$X_{\square c} = 5 \frac{\sqrt[4]{\lambda d_1}}{l \varepsilon_r},$$

where l is the length of the overlap, cm; ε_r is the relative dielectric constant of the glue; λ is the wave length, cm; d_1 is the clearance between the sheets (the thickness of the dielectric), cm.

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For example, let it be required that the shielding effectiveness be determined on a λ=150 cm wave by an aluminum sheet made of uniform foil 0.08 mm thick in two cases:

In the absence of the contact joint,

With a contact joint characterized by ℓ=5 cm, ε_r=5 and d_1=0.03 cm.

The surface resistance of the uniform foil is

$$R_{\square A}=\frac{\rho}{d}=\frac{2.6\cdot10^{-6}}{0{,}08\cdot10^{-3}}=0{,}32\cdot10^{-2}\ \text{ohms}.$$

The surface transition resistance of the contact is

$$X_{\square C}=5\,\frac{\sqrt[4]{\lambda d_1}}{\ell\varepsilon_r}=5\,\frac{\sqrt[4]{150\cdot0{,}03}}{5\cdot5}\approx0{,}2\ \text{ohms}.$$

The shielding effectiveness according to (1.16) will be

In the first case

$$\vartheta_{\square}=\frac{60\pi}{R_{\square}}=\frac{60\cdot3{,}14}{0{,}32\cdot10^{-2}}=6\cdot10^{3}\ \text{ or } 135\ \text{decibels},$$

In the second case

$$\vartheta_{к}=\frac{60\pi}{X_{\square C}}=\frac{60\cdot3{,}14}{0{,}2}=300\pi\ \text{or}\ 60\ \text{decibels}.$$

An obvious area for decreasing the transition resistance is increasing the length of the overlap b which, however, is limited by the consumption of material. In practice, the amount of overlap is limited to 5-7 cm. In necessary cases, glue with large ε_r is used. The use of electrically conducting glue is expedient.

For shields operating in a wide frequency band, beginning with 100 to 150 kilohertz, a combined contact joining of the thin sheets is used which is illustrated schematically in Fig 2.5, c. With this type of joining only the sections of overlap of length a are glued. As a result of tight joining of the sheets in the overlap section of length b, a rigid electric contact is also created. With a defined increase in the total length of the overlap a+b and a decrease in its glued part a the transition capacitance of the indicated contact retains its magnitude as a result of an increase in the number of plates of the formed equivalent capacitor.

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Consequently, on low frequencies the contact is insured predominantly by its active resistance, and on high frequencies, the transition capacitance.

The skin of the housings of the radio-electronic equipment is basically produced by the indicated methods, but in many cases the welding in a continuous weld can be replaced by spot welding or fastening the sheets with screws (bolts).

In all cases of joining of the sheets high finish of the treatment of the surfaces of the contact parts, dressing of the welded frame, the sheets of the skin, tight drawing them down with bolts are required. In the latter case, tin-plating of the contact points is recommended.

Spot welding and screw connections simplify the installation of the shield, but it is necessary to observe defined spacing between the fastening points; otherwise, slits of significant size will be formed which will lead to a reduction of its effectiveness. The required spacing of the fastening depends on the frequency band of the shield, the radiation power of the shielded source of electromagnetic oscillations or the required shielding effectiveness of the external field.

It has been established experimentally that the average number n of contact points per meter of contact length for insuring shielding effectiveness of Θ_0 is defined by the formula

$$\lg n = 1{,}2 - 0{,}2\lg\lambda + 0{,}25\lg(\Theta_0/5), \qquad (2.6)$$

where λ is the wave length, meters; Θ_0 is the required relative shielding effectiveness. The error in determining n by this formula does not exceed 30%, and the mean square deviation from the mean value is no more than 3 to 5 points.

In order to satisfy the norms for the biological shielding, the value of n must satisfy the condition

$$\lg n \geqslant \lg n_{\min} = 1{,}2 + 0{,}25\lg P - 0{,}2\lg\lambda, \qquad (2.7)$$

where n_{min} is determined with the same error, the wave length λ is expressed in meters, and the radiation power P in kilowatts.

It must be noted that in order to achieve a shielding effectiveness of more than 40 decibels with a wave length of less than 5 meters it is necessary to do away with the spot contacts and resort to using solid joints (solid seams) of the structural elements of the shield.

Some spatial versions of spot fastening of the skin sheets of the frame and other bearing structures of the radio-electronic equipment are presented in Table 2.4.

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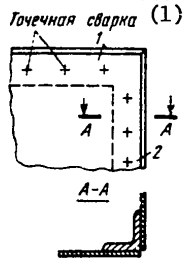
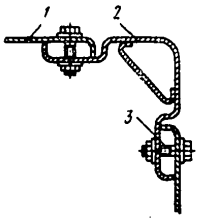
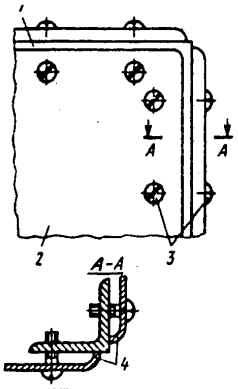
Table 2.4.

Versions of Spot Fastening of the Skin Sheets of the Radio-Electronic Equipment Frames

Sketch	Brief description
 Key: 1. spot welding	Fastening of the skin 1 to the frame by spot welding. Before welding the contact surfaces of the frame 2 and skin 1 must be cleaned, the skin sheets must be dressed and clamped tightly against the frame. The material thickness must not exceed 2 mm
	Fastening of the skin 1 to the frame 2 made of shaped sheets of steel by fastening bolts or screws 3. It is recommended that a small border be made along the edges of the skin panels which increases the rigidity of the panels and makes it possible to exclude openings in the intervals between the screws 3. It is used for shields with overall dimensions to 1-2 meters and effectiveness to 60 decibels.
	Fastening of the skin 2 to the frame 1 using fastening screws 3. The skin and the frame must be galvanized at the joining points 4. The contact points are not painted. It is used for shields with overall dimensions to 1-2 meters and effectiveness to 60 decibels.

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2.5. Shielding of the Openings

For normal functioning of the shield and the radio-electronic equipment elements in the shield, in particular, for achievement of the required thermal conditions of the shield structural elements it is necessary to provide the corresponding openings. The dimensions and location of the openings are determined by the purpose and the structural design of the shield and its operating characteristics. Sometimes holes are needed in the shield to match it to the structural design of the radio-electronic equipment or the radio engineering installation which includes the shielded assemblies and instruments, potential sources of interference or elements sensitive to it.

The openings in the shield together with the internal and external elements of the radio-electronic equipment, the internal and external space of the shield form ventilation, communication (for control, coupling and signalling) paths and channels for the transfer of different types of forces, fluids and gas. These channels must not interfere with the electric field of the shield or lower its effectiveness.

In order to insure the required effectiveness of the shielding the openings must be executed by the principle of limiting wave guides. As is known, the indicated principle consists in the fact that for defined relations between the dimensions of the wave guide and the wave length of the electromagnetic oscillations reaching its input, in practice the possibility of the propagation of these oscillations through it is excluded, that is, with respect to the oscillations at the input the wave guide system behaves as a filter with a delay band coinciding with the end where the basic part of the energy of their spectrum is concentrated. Part of the electromagnetic energy reaching the output of the wave guide determines the effectiveness of its operation as a filter, that is, the damping of this filter in the delay band.

In modern equipment various types of wave guide filters are used. However, in the electromagnetic shielding equipment basically the simplest find application: limiting wave guides which attenuate the oscillations with a wave length exceeding critical values $\lambda \geq \lambda_{cr}$, that is, high-frequency filters. These wave guides do not complicate the structural design of the shields and the elements of the radio-electronic equipment matched to them.

The high-frequency wave guide filter provides for damping in the delay band, for at frequencies below the critical frequency the wave front propagated in the wave guide has a constant phase, and the amplitude of the field intensity decreases by an exponential law on going away from the excitation source. The damping introduced by the wave guide with air filling per unit length (the running damping) is equal to the following [26]:

$$B\left[\frac{\text{дБ}}{\text{м}}\right] = \frac{54{,}6}{\lambda_{\text{кр}}}\sqrt{1-\left(\frac{\lambda_{\text{кр}}}{\lambda}\right)^2}, \qquad (2.8)$$

(1) (2)

Key: 1. decibels/meter; 2. cr.

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where $\lambda > \lambda_{cr}$ and λ_{cr} is expressed in meters. Formula (2.8) is valid for all types of waves and various forms of wave guides. The damping of the wave in the wave guide depends on the ratio λ_{cr}/λ. The limiting wave with a length greater than the critical wave in the wave guide is propagated with damping, for the front of the plane wave at $\lambda \geq \lambda_{cr}$ stands at an angle to the wave guide axis, and for very large wave length, in practice parallel to it. The plane wave in this case undergoes oscillations between the side walls of the wave guide along the axis of the wave guide, and the wave energy is propagated along the wave guide, decreasing more strongly the more parallel the wave front is to its axis. Inasmuch as the propagation path of the waves in the wave guide is always longer than in open space, the path which the wave travels inside the wave guide is greater than its length. Consequently, it remains to propose that the wave inside the wave guide is propagated, being reflected a multiple number of times from its walls, and its length of path therefore depends on the spacing between them, that is, on the wave guide dimensions. Obviously if on some frequency the wave is in practice only reflected from the wave guide walls without moving along it, then this frequency expresses the lower frequency limit of the oscillations which are not propagated in the given wave guide. The latter means that the part of the electromagnetic energy reaching the exit of the wave guide will not exceed the admissible values.

Thus, a wave guide can operate as a filter which effectively attenuates the oscillations on frequencies below the known limit, and to a significantly lesser degree attenuates the oscillations on frequencies above the given limit. Therefore the minimum damping introduced by the wave guide as a filter can be calculated by the formula

$$B_{min}\ [\text{дБ/м}] = \frac{54{,}6}{\lambda_{кр}}\sqrt{1-\left(\frac{\lambda_{кр}}{\lambda_{min}}\right)^2}. \qquad (2.9)$$

(1) (2)

Key: 1. decibels/meter; 2. cr

This means that the problem of designing a wave guide filter includes determination of its optimal dimensions beginning with the given λ_{min} in order to insure the required damping for unit length of the wave guide. Being given some value of $\lambda_{cr}/\lambda_{min}$, the dimensions of the wave guide determining λ_{cr} are connected with the upper boundary of the operating frequency band of the shield, that is, with λ_{min}. Then in this band, damping of no less than B_{min} is guaranteed inasmuch as the selection of the defined $\lambda_{cr}/\lambda_{min} < 1$ insures a shift of the delay band characterizing the wave guide as a filter within the limits of the spectrum of its input oscillations.

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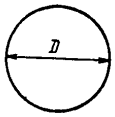
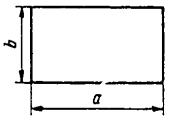
Table 2.5

Types of Waves and Their Damping in Various Wave Guides

(1) Тип волновода	(2) Волна	(3) $\lambda_{кр}$, м	(4) Затухание на единицу длины, дБ/м	(5) Затухание на длине l, дБ
	H_{11}	1,706D	32/D	32l/D
	E_{01}	1,307D	41/D	41l/D
	H_{01}	0,82D	67/D	67l/D
	H_{10}	2a	27,3/a	27,3l/a
	E_{11}	$\frac{2a}{\sqrt{1+(a/b)^2}}$	$\frac{27,3\sqrt{1+(a/b)^2}}{a}$	$\frac{27,3\sqrt{1+(a/b)^2}}{a}l$

Key:
1. Type of wave guide
2. Wave
3. λ_{cr}, meter
4. Damping per unit length, decibels/meter
5. Damping on a length ℓ, decibels

Formulas are presented in Table 2.5 for defined damping per unit length for various types of waves and wave guides with $\lambda_{cr}/\lambda_{min} \to 0$ or $\lambda_{cr}/\lambda_{min} \ll 1$.

As is known, in a wave guide of circular cross section the least damping is found for waves of the H_{11} type, and in a wave guide of rectangular cross section, H_{10} type. Therefore the calculation of the wave guide filters for the shields is carried out beginning with the condition of insuring the required damping for these types of waves. Then for other types of waves which can be excited in the wave guide, the damping will be higher than the minimum admissible value.

In shielding engineering, wave guide filters with rectangular cross section are finding broader application as being more technological in production and installation. In such wave guides for a wave of H_{10} with $\lambda_{cr}=2a$, we have

$$B_{min}\left[\frac{дБ}{м}\right]_{(1)} = \frac{54,6}{2a}\sqrt{1-\left(\frac{2a}{\lambda_{min}}\right)^2}. \qquad (2.10)$$

Key: 1. decibels/meter

In formula (2.10) it is convenient to take the large dimension a, meters, of the transverse cross section as the unit length. Then it is possible to write

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$$B_{\min}\left[\frac{\text{дБ}}{a_{(1)}\ \text{м}}\right]=27{,}3\sqrt{1-\left(\frac{2a}{\lambda_{\min}}\right)^2}. \qquad (2.11)$$

Key: 1. decibels/a, meters

This will be the damping of the wave guide for a length equal to its large dimension of the transverse cross section.

The graph of the functions $B=B(2a/\lambda_{min})$ has four characteristic intervals. In the interval $0<2a/\lambda_{min}\leqslant 0.1$, the damping is maintained in practice at the maximum possible level; here $a\leqslant 0.05\lambda_{min}$. In the range of $0.1<2a/\lambda_{min}\leqslant 0.4$, the damping decreases by comparison with the maximum value by approximately 1 decibel and in this case $0.05\lambda_{min}<a\leqslant 0.2\lambda_{min}$. For $0.4<2a/\lambda_{min}\leqslant 0.9$, the damping decreases by approximately 15 decibels and $0.2\lambda_{min}<a\leqslant 0.45\lambda_{min}$. Finally, in the range of $0.9<2a/\lambda_{min}\leqslant 0.999$, a sharp decrease in the damping takes place, the wave guide insures propagation of the wave in practice without losses, and in this case $0.45\lambda_{min}<a\leqslant 0.499\lambda_{min}$. Consequently, if we begin with the fact that the wave guide must insure high damping with comparatively large transverse cross section, then it is possible to consider the indicated relations optimal for the boundaries of the second and third intervals. Therefore it is assumed that the maximum value of the large dimension of the transverse cross section must be

$$a_{max}=0{,}2\lambda_{min}, \qquad (2.12)$$

and the wave guide can have any other dimension $a\leqslant a_{max}$. It is possible to decrease the value of a also within any admissible limits. The maximum admissible value of a_{max} in the long-wave band is 200 meters. In this band usually the structural dimensions of the wave guide are not limited. For example, instead of shielding the door opening in a shielded facility it is possible to use the open corridor with dimension a and wave guide length necessary to insure the required effectiveness.

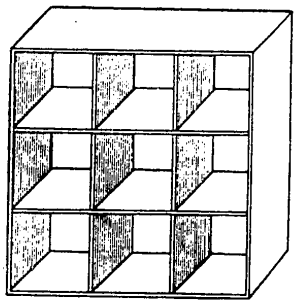

Figure 2.6. Wave guide filter of the honeycomb type.

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It does not always appear possible to adhere strictly to the relation (2.12) for various reasons. If this relation is not satisfied, then the damping losses can be compensated for by an increase in the length ℓ of the wave guide or by other measures.

Table 2.6 contains data for determining the dimensions of the wave guide filters insuring the required shielding effectiveness. These data are in practice realizable, checked during design and operation of shields for different purposes.

The most complicated of all is the problem of selecting the magnitude of a in the centimeter band, where as a result of the small value of λ_{min} the wave guide cross section can also be small. Some increase in the wave guide cross section is obtained by setting $2a/\lambda_{min}>0.4$, and a decrease in the damping in the wave guide in this case can be compensated for by an increase in its length.

Depending on the magnitude of the cross section of the wave guide filters determined by formula (2.12), two types of problems arise:

1) The cross section satisfies the channel parameters, but in order to obtain the given effectiveness, the length of the filter ℓ is found to be large, which complicates the structural design of the shield; 2) the cross section is small and does not satisfy the requirements imposed on the channel.

In order to resolve these difficulties, a wave guide filter of the honeycomb type was used (Fig 2.6). In this filter the total wave guide with large dimension a of the cross section is broken down into individual cellular wave guides with large dimension a_i of the cross section. Thus, if the wave guide forms a channel running through the shield, each individual cell and partial wave guide form a partial channel (subchannel) of this general channel. It is obvious that for each i-th subchannel, we must have $a_i<a_{max}$.

For identical cells, their number in the honeycomb type filter will be $n=S/S_{cell}$, where S is the total cross sectional area of the filter; S_{cell} is the cross sectional area of the cell (honeycomb).

If, in addition, the cross sections of the general wave guide cells are square, then $n=(a/a_{cell})^2$, where $a_i=a_{cell}$ for all i.

For the first case, when a is selected from (2.12), the total average effectiveness of the honeycomb type filter increases, and it can be defined by the experimentally obtained formula

$$\underset{(1)}{Э\ [дБ]} = 27{,}3 + 20 \lg \sqrt{n}, \qquad (2.13)$$

Key: 1. decibels

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Table 2.6

Data for Determining the Dimensions of the Wave Guide Filters

(1) Диапазон длин волн и минимальная длина волны λ_{min}	(2) Размер стороны волновода a, м, не более	(3) Затухание на 1 м длины волновода, дБ/м	(4) Длина волноводного фильтра для обеспечения эффективности экранирования Э, дБ					(5) Длина волновода, выраженная через эффективность экранирования, м
			30	40	60	80	100	
Long-wave λ_{min}=1000 m	$\lambda_{min}/100$	$27,3/a$	a	$1,5a$	$2a$	$3a$	$3,5a$	$Эa/27,3$
Medium-wave, 100 m	$\lambda_{min}/50$	$27,3/a$	a	$1,5a$	$2a$	$3a$	$3,5a$	$Эa/27,3$
Short-wave, 10 m	$\lambda_{min}/20$	$27,3/a$	a	$1,5a$	$2a$	$3a$	$3,5a$	$Эa/27,3$
Meter band, 1 m	$\lambda_{min}/10$	$26,6/a$	$1,1a$	$1,5a$	$2,2a$	$3a$	$4a$	$Эa/26,6$
Decimeter, 0.1 m	$\lambda_{min}/5$	$25,0/a$	$1,2a$	$1,6a$	$2,4a$	$3,2a$	$4a$	$Эa$ 25,0
Centimeter, 0.01 m	$\lambda_{min}/3$	$20,0/a$	$1,3a$	$2a$	$3a$	$4a$	$5a$	$Эa/20,0$

Key:
1. Wave length band and minimum wave length λ_{min}
2. Dimensions of a side of the wave guide a, meters, no more than
3. Damping per meter of length of the wave guide, db/meter
4. Length of the wave guide filter for insuring shielding effectiveness , db
5. Length of the wave guide expressed in terms of the shielding effectiveness, meters

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where 27.3 is the effectiveness of one cell for $a_{cell}=\ell$, decibels;
n is the number of cells in the general wave guide.

Formula (2.13) gives an estimate of the average effective cross section for n>8 to 10 with an error of no more than ± 3 decibels. The mean square deviation from the mean value does not exceed 1 decibel. The total length of the wave guide is

$$l=\frac{\Theta-20\lg\sqrt{n}}{B_{min}}, \qquad (2.14)$$

where B_{min} is the damping for 1 meter of cell length, decibels. It is obvious that in order to insure the required effectiveness, this length can be decreased as a result of the appearance of additional damping $20\lg\sqrt{n}$.

The situation is different in another problem where the cross section of the general wave guide is greater than the cross section determined by (2.12). In this case in the honeycomb design parallel paths appear for propagation of the electromagnetic oscillations, and the total wave guide damping diminishes:

$$\Theta=27{,}3-20\lg n. \qquad (2.15)$$

Formula (2.15) expresses the wave guide damping of a unit length ($a=\ell$). In order to compensate for the decrease in the damping, the total length of the wave guide is selected larger:

$$l=\frac{\Theta+20\lg n}{B_{min}}. \qquad (2.16)$$

Let us consider an example. Let it be required that the dimensions of the wave guide filter be determined insuring a minimum length of it. The frequency f=27 megahertz, the shielding effectiveness is no less than 52 decibels, the total wave guide cross section is 0.8x0.8 m^2.

In accordance with (2.12) we set $a_{max}=0.2\lambda_{min}=0.2\cdot 11=2.2$. If we take the length of the wave guide filter as $\ell=0.8$ meters, then the shielding effectiveness will be 27 decibels. For effectiveness of 50 decibels the length must be taken equal to 1.6 meter, which cannot be realized. Then let us use the honeycomb type filter. Let its cell size be 0.05x0.05 m; consequently, the number of cells is

$$n=\frac{0{,}8\cdot 0{,}8}{0{,}05\cdot 0{,}05}=256.$$

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The shielding effectiveness of this type of wave guide is

$$Э = 27{,}3 + 20 \lg \sqrt{n} = 27{,}3 + 20 \lg 16 \approx 51 \text{ decibels},$$

that is, it satisfies the given requirements for $a_{cell}=\ell$.

It is possible to calculate the wave guide length by (2.14):

$$l = \frac{Э - 20 \lg \sqrt{n}}{B_{min}} = \frac{52 - 24}{5{,}50} \approx 0{,}05 \text{ м},$$

where B_{min} is the damping for 1 meter of cell length, that is,

$$B_{min} = \frac{27{,}3}{0{,}05} \approx 550 \frac{\text{дБ}(1)}{\text{м}}.$$

Key: 1. decibels/meter

Structure and Installation of Wave Guide Filters. A wave guide is a tube of rectangular or circular cross section with conducting walls separating the channel in which the wave moves from the outside space (see Fig 2.7a). For a bent shape of the wave guide, the length of the midline is taken as a length. The wave guide is fastened to the shield by welding or soldering around the entire perimeter of the channel. The wave guide can be located both inside the shield and outside it. In addition, the wave guide can be divided by the shield in any ratio depending on the overall structural design of the system.

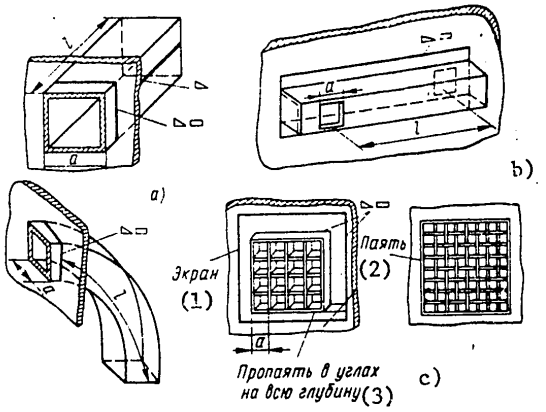

Figure 2.7. Installation of a wave guide filter on a shield

Key:
1. Shield; 2. solder; 3. solder to the entire depth at the nodes

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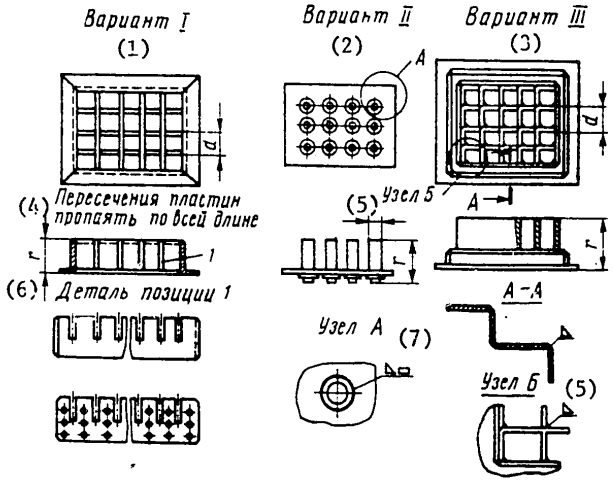

Figure 2.8. Versions of honeycomb devices

Key:
1. Version I
2. Version II
3. Version III
4. Plate intersections are soldered along the entire length
5. Assembly B
6. Position 1 detail
7. Assembly A

One of the wave guide walls can be the corresponding surface of the shield (Fig 2.7, b). Here the ends of the channel must be covered, and the distance between the middles of the entrance and exit of the openings is considered to be its length. When necessary, a honeycomb lattice is installed in one of the openings (see Fig 2.7, c), which is welded to the guide along the entire perimeter of the entrance (exit) opening.

The versions of the structural design of the honeycomb lattices are illustrated in Fig 2.8. Version I is made up of steel sheets. In the sheets, the length of which is determined by the channel dimensions (the width and length of the wave guide) slits with respect to the thickness of the material are made at a distance a. Then the lattice is assembled, and the joining points in each cell are fastened by welding or soldering.

Version II of the structural design of the lattice is assembled from segments of tubes of length ℓ and diameter d=a. Each tube is welded along the perimeter of its cross section to the sheet with the corresponding arrangement of the openings; version III of the lattice is a structural element made of angle steel.

2.6. Shielding by Perforated Materials

The ventilation openings of the louver type used in radio-electronic equipment are narrow slits which can intersect the paths of the currents

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induced in the shield, as a result of which the shielding effectiveness is diminished significantly. The measurements indicate that usually the louvers diminish the overall shielding effectiveness by 10 decibels or more. In order to eliminate this deficiency, a metal screen is attached under the louver on the frame on the inside. Usually the mesh of the screen is from 2x2 to 5x5 mm^2. However, almost all structural designs of this type are highly complex, and in many cases they do not insure the required power of the ventilation flows. Therefore these designs, as a rule, must be used only in equipment which is in installations requiring increased internal or external shielding.

Perforated inserts in the form of panels or discs are used in radio-electronic equipment. The perforated insert is made of a material which is thicker than the shield, and it is welded to the shield from the inside. On the outside the insert is enclosed in a frame. The perforated panel, jointly with the outside frame, can be fastened by bolts under the condition of insuring a tight contact along the entire perimeter of the panel, as illustrated in Fig 2.9. If a powerful air exchange is required, the cover and the bottom of the general shielding are made of perforated material.

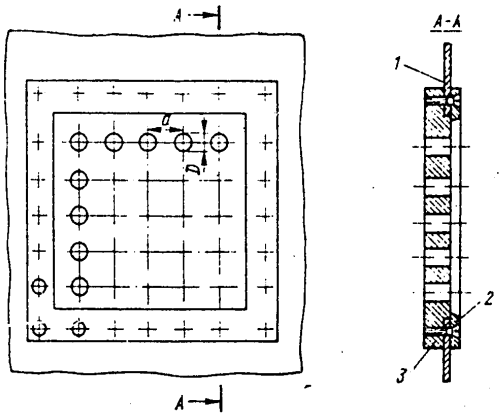

Figure 2.9. Sketch of the fastening of a perforated insert
1 -- shield; 2 -- outside frame; 3 -- perforated insert

The shielding effectiveness using perforated materials under the condition $\lambda >> D$ can be defined by the formula [39]

$$\vartheta_0 = \left(\frac{3\lambda_{min}a^2}{2\pi D^3}\right)^2 \approx \left(0{,}5\,\frac{a^2\lambda_{min}}{D^3}\right)^2, \qquad (2.17)$$

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where λ_{min} is the minimum wave length of the protected band; a is the spacing between the centers of the openings; D is the hole diameter.

The spacing between the centers of the holes usually is taken no less than 2D and no more than 6D. The maximum value of the hole diameter can be estimated from the condition $D_{max} < \sqrt[4]{\lambda^4_{min}/\vartheta^2}$. For longer waves, the admissible perforation hole size can turn out to be significant, and for smaller shields, the total shielding effectiveness can be reduced significantly. Therefore we shall limit ourselves to hole sizes of 2 to 3 cm.

In the centimeter wave band, as a result of the small hole diameter, the structural design of the channel can fail to satisfy the technical requirements. Inasmuch as the perforated insert is represented as a lattice of limiting wave guides, some expansion of the openings can be obtained by increasing the thickness of the perforated material.

2.7. Filtration of Electric Networks with Electromagnetic Shielding

The shielding is one of the basic measures of attenuation and localization of electromagnetic fields in the interest of increasing the operating stability of the radio-electronic equipment. However, the effectiveness of the shielding depends to a significant degree also on the filtration of the electric control, signal, coupling and electric power supply networks passing through the shield, introduced into the shield and exiting from it. The operating fitness of any fairly improved shield will be reduced significantly if the propagation of the electromagnetic oscillations outside or inside the shielded space along these networks is not prevented. Consequently, the filtration of the electric networks and lines is a technical measure corresponding to the electromagnetic shielding in the majority of its applications, and the devices providing this filtration must be an inseparable part of the shielding system.

Inasmuch as these devices are designed to suppress the oscillations in the radio frequency band, their basic function is the so-called radio frequency filtration in contrast, for example, to the attenuation of the pulsations in the DC power supply network, and so on.

Let us assume that the electromagnetic energy goes beyond the limits of the shielded space or enters it only as a result of imperfection of the shield and insufficient filtration of the network. Then if the total effectiveness of the shielding system or the interference suppression system is given, it is clear that the partial effectiveness of the shielding itself and the filtration accompanying it in the general case must be no worse than the resultant effectiveness of the system as a whole. The losses of effectiveness of interference suppression and expenditures will be minimal if both these partial effectivenesses are taken to be equal. Inasmuch as with respect to difficulties of realization the partial effectiveness of the shielding itself is first, the filtration effectiveness is equated to it in the general case.

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In all cases the filtration effectiveness must be considered taken into account the matching of the filter with respect to the input (with the input signal generator) and the output (with the load), that is, depending on the characteristics of the internal impedance Z_i of the interference source and the load impedance $Z_н$ (see Fig 1.4).

The filters of the electric circuits entering into the shielded space or passing through it are placed both inside and outside the shields and the equipment. The filters, as a rule, are not tunable, and they are not switchable. The following requirements are imposed on them, which arise from the specific conditions of application:

Small losses in the transparency band and sufficiently high damping in the entire delay band taking up a very broad interval of the radio frequency band (sometimes within the limits from 0.1 to 10^4 megahertz);

The capacity to operate efficiently in the case of strong transmitted currents, high voltages, high power levels of the transmitted and suppressed electromagnetic oscillations, and for the filters in the electric power supply networks, high power levels of direct or alternating current of industrial and other frequencies;

The capacity to maintain the basic technical specifications in the pass bands and the suppression bands during mechanical and climatic loads, which can be uncharacteristic of other equipment of the installations and shields.

The indicated requirements mean that the elements of the electric circuit filters of the shielding systems form a separate group of electroradio elements from the point of view of their purpose and conditions of application, the basic and secondary parameters of which are considered in wide frequency bands, wide ranges of currents, voltages, powers and large variations of temperature, humidity, impact and vibration loads, and so on. These elements, just as the filters themselves, are called interference suppressing or shielding elements.

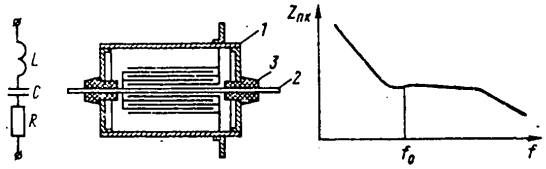

Figure 2.10. Sketch of the device, equivalent circuit diagram and form of the frequency characteristic of the transmitting capacitor

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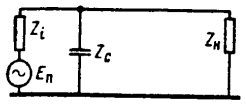
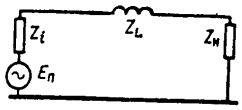
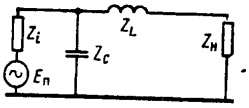
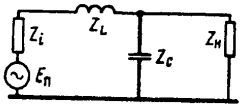
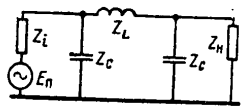
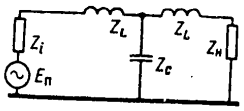
Table 2.7

Basic Types of Low-Frequency Filters and the Formulas for Estimating the Introduced Damping

Equivalent circuit diagram of the filter	Introduced damping
Эквивалентная схема фильтра	Вносимое затухание
	$B_C \approx \frac{z_н}{z_i + z_н} \frac{z_i}{z_C}$; for $z_i \ll z_н$ $B_C \approx z_i / z_C$
	$B_L \approx \frac{z_н}{z_i + z_н} \frac{z_L}{z_н}$; for $z_н < z_i$ $B_L = \frac{z_L}{z_i}$
	$B^г_{CL} \approx \frac{z_н}{z_i + z_н} \frac{z_i}{z_C} \frac{z_L}{z_н} \approx \approx \frac{z_i + z_н}{z_н} B_C B_L$; for $z_i \ll z_н$ $B^г_{CL} \approx B_C B_L$
	$B^г_{LC} \approx \frac{z_н}{z_i + z_н} \frac{z_L}{z_C} \approx \approx \frac{z_i + z_н}{z_i} B_L B_C$; for $z_н \ll z_i$ $B^г_{LC} = B_L B_C$
	$B^п_{CL} \approx \frac{z_н}{z_i + z_н} \frac{z_i}{z_C} \frac{z_L}{z_C} \approx \approx \frac{z_i + z_н}{z_i} B^г_{CL} B_C$; for $z_н \ll z_i$ $B^п_{CL} \approx B^г_{CL} B_C$
	$B^г_{LC} = \frac{z_н}{z_н + z_i} \frac{z_L}{z_н} \frac{z_L}{z_C} \approx \approx \frac{z_i + z_н}{z_н} B^г_{LC} B_L$; for $z_i \ll z_н$ $B^г_{LC} \approx B^г_{LC} B_L$

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In the shielding systems basically low-frequency filters are used. The equivalent diagrams and formulas for estimating the damping introduced by these filters are presented in Table 2.7. As is obvious from the data presented in the table, in order to obtain sufficient damping it is expedient to use primarily inductive-capacitive filters. The application of only one capacitance or inductance as the filter has meaning only in certain cases. The blocking of the electric power supply network by a capacitance is effective when the internal resistance of the interference source and the network is high. The shielding using an inductance can occur in the opposite case when the internal resistance of the interference source and the network is low. The L-type filter with capacitive input is used when the internal resistance of the interference source is large, and the network resistance is small. The L-type filter with inductive input is expediently used in the opposite situations. The Π-type inductive capacitive filters have become the most widespread for the filtration of the power supply networks, inasmuch as for other in practice equal indexes they turn out to be less complicated with respect to structural design and insure quite high damping of the interference.

Interference Suppressing Capacitors. The total resistance of a capacitor in a wide frequency band is determined not only by its capacitance, but also by the inductance of its leads. The equivalent diagram of the capacitor can be represented in the form of a series circuit (see Fig 2.10, a).

Thus, each capacitor has a defined resonance frequency, above which its total resistance is determined not by the capacitance, but by its natural inductance. In order to expand the frequency band in which the total resistance of the capacitor will not exceed a defined value, it is necessary to decrease the natural inductance of the capacitor. In addition, requirements are imposed on the capacitors, depending on the operating conditions, with respect to moisture resistance, heat resistance, electrical and mechanical strength, and so on. At the present time industry is producing special interference suppressing capacitors type KZ. These capacitors have a natural inductance of less than $50 \cdot 10^{-9}$ henries. However, in a number of cases, in view of the insufficiently broad nomenclature of the type KZ capacitors and also as a result of the restrictions with respect to weight and size it is necessary to use ordinary capacitors. Among them, for filtration of the interference-carrying networks it is recommended that the KSO and KBG type capacitors, and so on be used. If the ordinary capacitors are used to include an alternating current in the network, then it is necessary to consider that their rated operating voltage is indicated only for direct current.

The application of the KZ type capacitors and ordinary capacitors is limited to frequencies of 10 to 20 megahertz. At higher frequencies, their use, as a rule, has low efficiency.

For the suppression interference in the frequency range above 10 to 20 megahertz, it is recommended that duct capacitors be used. These capacitors, for example, KBP type (All-Union State Standard 6760-62) have

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a number of peculiarities which must be discussed in more detail. With respect to structural design the duct capacitor differs significantly from the ordinary one (see Fig 2.10, b).

The current-carrying rod passes through the housing of the capacitor and is insulated from it by porcelain or glass insulators. One end of the section is soldered to the current-carrying rod, and the other around the entire perimeter, to the housing which is one of the leads of the capacitor.

For the characteristic of the duct capacitor, a parameter is introduced equal to the ratio of the output voltage (in the absence of a load at the output) to the input current and, consequently, having the dimensionality of resistance. This parameter equal to the resistance modulus $Z_{\pi k}$ of the equivalent circuit is called the resistance of the duct capacitor.[1]

The frequency dependence of the resistance of the duct capacitor having capacitive nature in a wide frequency range is presented in Fig 2.10, c. In the frequency range below f_0, the magnitude of the duct capacitor resistance is basically determined by its capacitance. In this frequency range the duct capacitor almost does not differ from the ordinary one. However, in the frequency range above f_0 the modulus of the resistance $Z_{\pi k}$ reaches very small values (to 10^{-3} ohms). In this frequency range the duct capacitor operates as a voltage divider, the interference-suppressing properties of which improve with an increase in the frequency. This is the basic advantage of the duct capacitor permitting its use in a wide frequency band.

The interference-suppressing properties of the duct capacitor depend very significantly on its arrangement and its method of attachment. The duct capacitor is arranged so that the input and output circuits will be effectively shielded. It must be installed on the plane of the shield separating the input and output circuits (the installation of the duct capacitor on the removable part of the shield is not permitted) (see Fig 2.11).

The high interference-suppressing properties of the duct capacitor in the frequency range above f_0 can be achieved only with proper fastening of it, that is, with linear or multipoint contact of its housing with the shield around the entire perimeter of the housing. In order to attach the duct

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[1] This term is used in the text of the All-Union State-Standard 6760-62, but other terms are encountered in literature and practice: basic resistance, coupling resistance, total resistance of the duct capacitor, and so on. The term coupling resistance is obviously the best, for it reflects the sense of the parameter as a characteristic of the coupling of the input of the duct capacitor to its output. Strictly speaking, $Z_{\pi k}$ is the modulus of the corresponding resistance.

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capacitor to the shield on the housing there is a flange, a thread or bracket.

The duct capacitors are intended for use in DC or AC, industrial frequency circuits. The capacitors with threaded connection are made for an operating current to 10 amps and rated DC voltages of 125, 250 and 500 volts, which corresponds to 50, 127 and 220 volts AC; their rated capacitances are 0.022 to 0.1 microfarads. The capacitors with flange fastening or bracket fastening are made for rated voltages of 125 to 1600 volts DC, which correspond to 50 to 500 volts AC, for an operating current of 20, 40 and 70 amps and a capacitance of 0.022 to 2.0 microfarads. Depending on the rated voltage and the capacitance, the housing of the KBP capacitors has a diameter of 14 to 40 mm and a length of 55 to 126 mm.

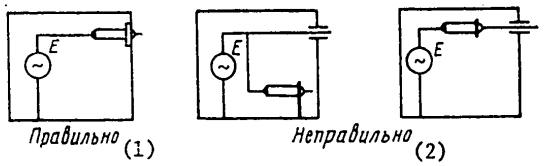

Figure 2.11. Examples of the installation of a duct capacitor

Key:
1. Correct
2. Incorrect

Since the soldering of the housing of duct capacitors to the shielding usually is not used, the threaded fastening is one of the best. It is desirable to use flange fastening with no less than 6 screws, paying special attention to see that the contact surface of the flange and the shield are clean and tin-plated or zinc-plated. The placement of foil between the flange and the shield can be recommended (if this is permitted by the production process) only in the case of using tin foil. The hole in the shield for the current-carrying rod of the duct capacitor must be completely closed by the duct capacitor flange. The fastening of the KBP type capacitor by a bracket is the worst, for it does not satisfy the above-indicated requirements.

Interference-Suppressing Chokes. Interference-suppressing chokes can be used both as independent filtration devices and in the form of the component parts of the filter. They are installed directly at the source of the interference or near it and they are included in the low-frequency filters in series with the conductor through which the interference is propagated. The quality of the choke to a significant degree determines the advantages of the filter.

A characteristic feature of the operation of the choke in shielded filters is the fact that they must have sufficiently large resistance in a wide frequency band. However, for the satisfaction of this requirement on low

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frequencies it is necessary to make the coils with significant inductance and a large number of turns as a result of which the natural capacitance of the coils increases, decreasing their resistance at high frequencies. The application of the sectional windings in the coils lowers their natural capacitance, but it also decreases the inductance. Thus, it is necessary to find a compromise solution. In avoiding the losses it is necessary to strive to have the active resistance of the coil be minimal.

When designing chokes for the filters of the shielding system it is also necessary to remember the insurance of sufficient mechanical strength, insulation and moisture resistance. In addition, it is necessary to try to reduce the coil dimensions, insure a large cooling surface to limit heating, decrease the consumption of nonferrous metals, for example, copper and insulating materials. In some cases the chokes are shielded. Usually the natural frequency of the choke is selected equal to the average frequency of the shielded band. Here it is possible to have the value of the total resistance of the choke not exceed the admissible limits. In order that the frequency characteristic of the filter be as uniform as possible in the required frequency band, it is not necessary to use large inductances. In the majority of cases the inductance of the chokes must not exceed 500 microhenries. Their structural design is such that the natural capacitance will not exceed 100 picofarads. Any chokes having the necessary frequency characteristics of the total resistance can be used as the interference-suppressing chokes.

The choke can be both with ferromagnetic core and without it. VCh-2 steel is recommended as the core material, the magnetic permeability of which remains significant even in the high frequency range. In order to insure high permeability at high frequencies with small currents flowing through the choke, it is recommended that farads be used as the core, which, while retaining the required inductance, permits significant decrease in the choke dimensions (the number of turns).

In order to determine the inductance of a coil of circular cross section, the following formula is used [40]:

$$L\ [\text{мкГ}] = \frac{(\pi n D)^2}{l + 0{,}45D} \cdot 10^{-3}. \qquad (2.18)$$

The presented formula insures the necessary accuracy for practice under the conditions that $\ell > 0.3D$. For $\ell \gg D$, the formula is simplified and assumes the form

$$L\ [\text{мкГ}] = \frac{(nD)^2}{100l}. \qquad (2.19)$$

(1)

Key: 1. microhenries

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The inductance of the multilayered cylindrical choke with a winding of the universal type or with a bulk winding [40] is:

$$L\ [\underset{(1)}{\text{мкГ}}] = \frac{0{,}08\,(n\overset{(2)}{D_{\text{ср}}})^2}{3D_{\text{ср}} + 9l + 10c}, \qquad (2.20)$$

Key: 1. microhenries; 2. mean

where D_{mean} is the mean diameter of the coil, cm; ℓ is the length of the coil, cm; c is the thickness of the coil, cm; n is the number of turns.

In order to filter the high-power electric power network, the choke inductance on a frequency of 0.25 megahertz usually does not exceed 10 microhenries. The application of ordinary coil chokes under these conditions is limited by the technical difficulties connected with the use of high currents. These difficulties are eliminated by using coilless chokes.

This type of choke is a rectilinear, current-carrying rod surrounded by a magnetic circuit in the form of a thick-wall tube made of ferromagnetic material.

The inductance of the coilless choke is determined by the magnetic flux passing through the magnetic circuit under the effect of the current [23]:

$$L = 0{,}2\mu_r h_{\text{м}} \ln (d_2/d_1), \qquad (2.21)$$

where μ_r is the initial magnetic permeability for the given magnetization current, microhenries/m; h_M is the length of the magnetic circuit, meters; d_2 is the outside diameter, d_1 is the inside diameter of the magnetic circuit, meters.

For calculations by formula (2.21), it is necessary to consider the dependence of the magnetic permeability on the frequency for different magnetization currents into set $d_2/d_1 < 4$.

Elements of the Ultrahigh and Superhigh Frequency Filters. As is known, the generality of the basic results of the theory of filters is varied for all frequency bands. However, the specific characteristics of the microwave circuits such as the periodicity of the frequency characteristics, the presence of high types of waves and the variety of initial elements with known properties require a defined approach to these circuits directed either at using the indicated additional properties or correction and suppression of them.

The coils and capacitors on ultrahigh frequencies and microwave frequencies are replaced by resonance segments of long lines, coaxial, wave guide and volumetric resonators. The introduced losses are considered beginning with the concept of the voltage standing wave coefficient. The damping of the oscillations in the microwave range is caused by the phenomenon of simulation of the surface effect.

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The standard microwave filter used in the shielding system is a low-frequency filter in the form of a coaxial line included in the interference-carrying network. The suppression band of the filter is in the microwave range where the required damping must be insured.

The structural design of the filters usually is such that the microwave currents pass through a thin electrically permeable film applied to the inside surface of the dielectric tube with a high value of the dielectric constant ε_r, and the currents on frequencies below the filter cutoff frequency, including direct current and industrial frequency current, pass through the central conductor of the coaxial cable.

The creation of different paths for the ultrahigh frequency or microwave currents and currents on frequencies in the pass band of the filter is based on the surface effect.

The equivalent circuit of the elementary filter simulating the skin effect is the parallel connection of two quadripoles. One of them has very large losses as a result of the high value of ε_r. It is an electrically long line, the physical length of which, however, is short. The second quadripole is equivalent to an internal conductor -- the rod used to transmit the currents on frequencies below the cutoff frequency of the filter.

Already on frequencies above 300 megahertz, it is very complicated to obtain a lumped high Q-factor inductance, and on frequencies above 1 to 2 gigahertz, lumped capacitance. Therefore when concentrating the interference energy near 400 to 300 megahertz and higher, the corresponding filters are made, as a rule, with distributed parameters. By varying the electric or physical length of the line, the resistance of the corresponding nature is obtained.

Absorbing material plays an important role in designing ultrahigh frequency and microwave filters. Various types of ferrites, carbonyl iron, Alsifers and so on are used as such materials. It is necessary to consider a suspension of powdered magnetic alloys in an epoxy compound as the most effective material. The absorbing materials can be placed in the filter in many ways. For example, in a coaxial filter the absorbing material is in the form of washers in a metal housing fitted on the current-conducting rod. The number of washers is determined by the required amount of interference suppression.

Thus, the basic elements of the low-frequency filter for ultrahigh frequency and microwave bands are elements with distributed parameters, the characteristics of which are determined by their arrangement and overall structural design.

The problems of designing ultrahigh frequency and microwave filters are investigated in detail in [41, 42]. However, it is necessary to consider that as applied to the shielding systems, these filters in many cases

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must be calculated for comparatively high levels of transmitted power and satisfy other requirements indicated above.

2.8. Application and Structural Designs of Filters

The effectiveness of each of the filters included in the interference-carrying networks must not be below the overall effectiveness of the filtration system as a whole, which, in turn, must not be less effective than the shield. The obtaining of the most improved filter characteristics arises from the corresponding development of its structural design.

The structural design of the filter is basically determined by its effectiveness, purpose and placement with respect to radio-electronic equipment and shield. When developing the filter design the following are considered: 1) the total number and mutual arrangement of the potential sources of interference inside and outside the equipment, 2) the frequency band, spectral and other characteristics of the interference sources, the overall noise level, and the directionalness of the propagation and the emission of the interference.

These two factors basically determine the conditions of use of the filter and the required effectiveness of the filtration of the interference in the corresponding sections of the radio frequency band and, consequently, offer the possibility of developing the requirements on the structural design of the filter, its parameters and the filtration system as a whole.

The filtration system is developed simultaneously with the shielding system. Analogously to how the point of installation of the shield and the type of shielding are determined in the operating circuit, the problem of the methods of filtering the networks, individual devices and equipment as a whole is also solved. The filtration system must provide the required effectiveness with a minimum number of filters and the simplest structural design. With respect to purpose, the filtration systems can be divided into three groups: systems for localizing the electromagnetic oscillations and radiation within the installation (shield), systems for eliminating mutual interference, spurious couplings and inductions in radio-electronic equipment and systems for insuring interference suppression of the radio receiving and transmitting devices and the automation of the radio-electronic means.

In the first case the filtration is realized by inclusion of filters of various types belonging to the given shielding at the input (output) of the power supply, control and communications networks. The second type of filtration is intrasystem with respect to the entire volume or all of the equipment, and it is realized by simple filters or individual interference-suppressing elements. The third system is similar to the first except that the filtration can be intrasystem and external with respect to the given type of radio-electronic means or group of radio-electronic means.

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The installation of the complex radio engineering or industrial systems with shielding and filtration belongs to the second group, and therefore the number of filters can be decreased with corresponding mutual arrangement of the equipment and power supplies, the spatial separation and laying of the cables. The network introduced into the shielding in shielded cables can be left unfiltered, for example, the networks designed for transmitting specially shaped signals with small admissible distortions. When designing the radio frequency shielding filters used in the interference-carrying circuits passing through the shields, three basic problems arise, the joint solution of which is a necessary condition of obtaining optimal frequency-amplitude characteristics.

The first problem consists in the necessity of matching the filter with respect to its input and output with the channel parameters where it is connected in a sufficiently broad frequency band. This problem is solved by the methods of wide-band matching and other methods discussed in electric circuit theory.

The second problem consists in considering the partial or complete degeneration of the filter, the circuits and high frequency load preceding it from elements with lumped parameters to elements with distributed parameters and the reverse phenomenon on low frequencies. Here by low and high frequencies we mean the frequencies differing by one or more orders from the cutoff frequency of the filter. This problem is solved by selecting the circuit diagram and elements of the filter with the corresponding frequency characteristics, the construction of an expedient filter design with a high radio engineering level of installation. In particular, in order to attenuate the effect of the indicated phenomena of degeneration of the electroradio elements, so-called combination filtration systems can be used which are combinations of series and parallel inclusion of filters of various types for different frequency bands. Each of these filters insures and corrects the defined part of the resultant frequency-amplitude characteristic of the general filter or filtration system as a whole.

The essence of the third problem is determined by the presence of spurious couplings of the filter elements to each other and the adjacent assemblies of the radio-electronic equipment with respect to the theoretical circuit or structural design. The spurious couplings, being numerous and random with respect to their nature, also lend a random nature to the filter damping as a function of frequency and its other parameters, inasmuch as they obtain the random components of their values. Therefore the first step in the operation consists in eliminating the effect of random factors. Among the numerous measures of controlling spurious couplings of the radio-electronic elements, the primary role is played by electromagnetic shielding. As applied to the shielding filters, element by element, modular and total shielding are used. The shielding of the filter elements, the separation of the filter input from the output and also shielding of the filter as a whole insure increased damping and decreased nonuniformity of the frequency-amplitude characteristics in a wide suppression band. Thus, it is possible

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to raise the damping in the suppression band from 20-40 to 60-70 decibels or higher. The problem of selecting the type of shielding for the filter is solved beginning with its purpose, its circuit diagram and structural design, operating conditions and the requirements on it.

For defined relations between the power level passing through the filter and its overall dimensional characteristics, the necessity arises for forced cooling of the filtration system elements. The use of liquid cooling for these purposes promotes increased shielding effectiveness.

Thus, the shielding of the filtration elements on the one hand determines the filter characteristics, suppressing the effect of the random factors, and on the other hand, permits improvement of these characteristics.

Depending on the number of filtered conductors, the filters can be single wire, two-wire, three-wire, and so on. In addition, depending on the arrangement and structural design the filters can be divided into attached filters and built-in filters.

The attached filters are usually installed beside the source of the interference on its housing and are not necessarily designed for the given interference source.

The built-in filters are designed for the specific electroradio device, which is the source of the interference, and it is in the form of an integral structure with it.

The basic operating criterion of the shielding filter when it is included in the degree of attenuation of the interference voltage on the load resistance achieved by it. It is possible to evaluate the filter both with respect to its natural and operating attenuation. However, it is necessary to consider that the natural attenuation always has an effectiveness margin, and the operating attenuation depends on the load resistance. The operating attenuation can be determined by the formula

$$b_p = 20 \lg (U_1 / U_2),$$

where U_1 is the interference voltage measured on the generator terminal (at the filter input); U_2 is the interference voltage measured at the filter output with the load included.

The following basic requirements on the shielding filters are formulated in the technical documentation:

The magnitude of the operating voltage and current of the filter must correspond to the voltage and current of the filtered network;

The magnitude of the operating attenuation must not assume values less than admissible in the shielded frequency band;

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The voltage drop in the inductive-capacitive filters must not exceed the admissible values;

The structural design of the filters must provide for attachment of them to the interference source and be repairable;

Minimum weight and size of the filters must be realized;

Resistance to mechanical loads and the possibility of operating with defined relative humidity in the given temperature range must be insured;

The structural design of the filters must correspond to the safety engineering requirements.

The indicated requirements are closely interrelated, but they contain a number of contradictions. Therefore when designing filters the choice of the circuitry, the structural design and the parameters is made beginning with compromise arguments.

The effectiveness of the filters essentially depends on the structural design and the installation of the elements. When designing the filter and when installing the interference suppressing attachment (independently of whether they are filter elements or any interference suppressing system) it is necessary to consider the following recommendations.

1. As a rule, the filter must be shielded (this requirement is not mandatory for capacitive filters executed from ordinary capacitors). Usually the shield for the filter is its housing which must be executed in accordance with the requirements indicated above.

2. The input and output lines must be introduced into the filter housing from opposite sides and run outside the housing as far from each other as possible. If on the input or output lines there is a shielded braid (or tube), the latter must have a reliable contact with the filter housing along the entire perimeter of the opening for entrance of the conductor (the contact is realized best of all by soldering).

3. A great deal of attention must be given to shielding the input and output circuits of the filter, including the input and output capacitors, especially if these capacitors are duct capacitors and are located at the input and output of a multielement high-efficiency filter. The shielding of the middle elements in the multielement filter of the electric power supply circuit from each other is not mandatory.

4. It is necessary to avoid arranging the filter elements on the removable parts of its housing (covers, and so on).

5. The duct capacitor must be placed and fastened as described above.

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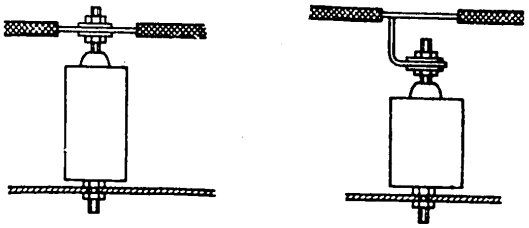

Figure 2.12. Examples of a duct installation

6. The ordinary capacitors and the shielded type KZ capacitors are recommended for installation by the so-called duct method, that is, connection of the interference-carrying conductor directly to the capacitor output (see Fig 2.12). If the capacitor housing serves as one of its leads, then the fastening of the capacitor housing to the frame or to the housing of the filter must insure a reliable contact. For this purpose the housing or frame of the filter must at the point of fastening the capacitor housing have a tin-plated or zinc-plated surface. If one of the leads of the capacitor must be connected to the frame or the housing of the filter, then this connection must be made by the shortest possible wire (no longer than 10 to 15 mm) of sufficiently great diameter (no less than 2 mm). The wire is best of all soldered to the frame. When it is impossible to connect the capacitor lead to the filter housing by such a short wire, it is recommended that this connection be made using buses or wired mats.

7. The attachment of the capacitors and chokes must be mechanically strong and vibration-resistant, for vibration can lead to breaking of the contact of the filter elements with the housing.

8. In the case of using unshielded chokes it is necessary to correctly place them with respect to the capacitors and the conductors connected to them.

9. It is impossible to use a capacitor lead for its mechanical fastening.

10. The interference suppressing attachments (chokes, capacitors and other parts) must be placed so that there is access to inspect them, check them and replace them.

11. The capacitors which can remain charged on disconnection of the equipment from the power supply network must have discharge resistances through which the capacitors must be discharged no later than 10 seconds after disconnection of the equipment.

For suppression of interference in the ultrahigh frequency and microwave bands, usually the untunable low-frequency filters are used. With respect

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to structural design, the microwave protective filters usually are coaxial, and with respect to operating principles, absorbing. In the design of such filters, an important role is played by the selection of the absorbing material and the spacing between its particles in pressed form, for these purposes in the majority of cases powdered magnetic alloys are used made up of metal particles coated with oxide or phosphate film. The particles are distributed in the binder of the epoxy resin type. By varying the spacing between particles it is possible to change the distribution of the eddy currents and, consequently, the damping of the filter.

The choice of parameters of the capacitors and chokes used both as filter elements and as interference-suppression elements is made on the basis of calculating the filter. However, it is difficult to perform this calculation precisely in the majority of cases, for the parameters of the equivalent circuit needed for the calculation can be unknown. Therefore it is recommended that the final choice of the choke and capacitor parameters be made after experimental checking during normal operation of the equipment and the shielding system.

Several series of interference-suppressing filters designed for filtration of power networks, monitoring networks, communication, control and signalling networks, and so on have been developed and are being produced industrially.

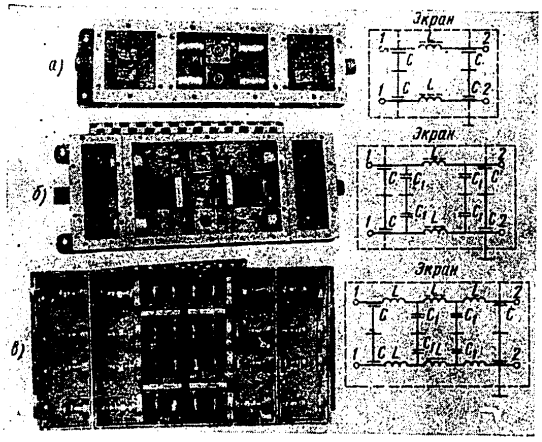

Figure 2.13. General views and circuit diagrams of the FP type filters with an effectiveness of no less than 60 decibels (a); no less than 80 decibels (b); and no less than 100 decibels (c)

Key:
1. Shield

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FP Type Filters. The FP type electric filters are attachment-type filters. They are designed for operation in the frequency band of 0.15 to 1000 megahertz with an effectiveness of the interference suppression of 60, 80 and 100 decibels. The nomenclature includes 18 types of filters designed for various operating loads and DC and AC voltages. The normal operation of the FP filters is guaranteed at an ambient temperature of -50 to +50°C and a relative humidity of the air of 98% at a temperature of +44°C. They are symmetric П-type low-frequency filters with respect to the electric circuit diagram. The filter elements have lumped parameters. The KBP duct capacitors and the KBG-MN capacitors are used as the capacitive elements, and special chokes are used as the inducting elements. As is obvious (Fig 2.13), the filters are made in the form of metal boxes separated inside by shielding partitions into three separate compartments tightly closed by covers. In the middle, basic compartment are the circuit elements. In the edge compartments are the clamping frames to which the filtered cables and conductors are connected. The basic parameters of the FP filters are presented in Table 2.8.

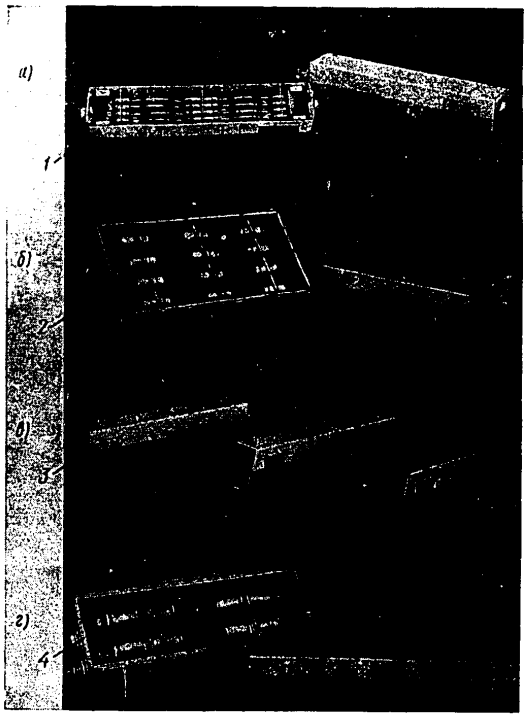

Figure 2.14. General views of some FB-1M filters (1); FB-4 (2); FB-5 (3); FB-6M (4)

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Table 2.8

Basic Characteristics of the FP-Type Filters

(1) Тип фильтра	(2) Рабочий ток, А	(3) Рабочее напряжение, В			(7) Габариты, мм³	(8) Масса, кг	(9) Тип сердечника дросселя; индуктивность, мкГ	(10) Емкость конденсаторов, мкФ	
		Постоянный ток (4)	50 Гц (5)	400 Гц (6)				КБП проходной (11)	КБТ-МН (12)
(13)ФП-1	2,5	500	220	115	350×100×60	2,4	(14)СБ-3; 400	0,22	—
ФП-2	4	250	127	65	350×100×60	2,4	СБ-5; 160	0,47	—
ФП-3	4	500	220	115	430×150×80	5,0	СБ-5; 160	0,47	—
ФП-4	4	1600	500	250	430×150×80	6,4	СБ-5; 400	0,22	—
ФП-5	10	500	220	115	430×150×80	5,4	СБ-5; 25	1,0	—
ФП-6	20	500	220	115	430×150×80	5,5	СБ-5; 26	1,0	—
ФП-7	1,0	250	117	65	430×150×80	4,8	СБ-3; 400	0,47	—
ФП-8	2,5	1500	500	250	470×170×80	6,2	СБ-5; 1000	0,22	2×0,5
ФП-9	4,5	1000	380	190	470×170×80	6,1	СБ-5; 400	0,47	2×0,5
ФП-10	10	500	220	115	470×170×80	6,1	СБ-5; 63	1,0	2×1,0
ФП-11	16	1000	380	190	560×210×80	8,5	СБ-3; 160	0,47	2×0,5
ФП-12	20	500	220	115	560×210×80	8,5	(15)ПЛ; 63	1,0	2×0,5
ФП-13	20	1500	500	250	560×210×80	9,5	ПЛ; 160	0,22	2×1,0
ФП-14	40	1500	500	250	560×210×80	10,5	ПЛ; 63	0,22	2×1,0
ФП-15	70	500	220	115	880×370×150	40,5	Безвитковый; 6	1,0	2×1,0×4,0
ФП-16	150	500	220	—	980×420×150	70,0	" "	2,2	4,0
ФП-17	150	1000	380	—	1030×280×150	45,0	(16)" "	1,0	2×1,0; 4,0
ФП-18	600	1000	380	—	1030×530×150	80,0	" "	2,2	4,0

Key:

1. Type of filter
2. Operating current, amps
3. Operating voltage, volts
4. Direct current
5. 50 hertz
6. 400 hertz
7. Overall dimensions, mm^3
8. Mass, kg
9. Type of choke core; inductance, microhenries
10. Capacitance of the capacitors, microfarads
11. KBP duct capacitor
12. KBT-MN capacitor
13. FP ...
14. SB ...
15. PL ...
16. Coilless

Notes. 1. The FP-15 and FP-16 filters are four-wire filters; the rest are two-wire filters.

2. The operating attenuation under active load of 50 ohms for the FP-1 to FP-6 filters is 60 decibels, for the FP-7 to FP-11 filters, 80 decibels, and for FP-12 to FP-18, 100 decibels.

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Table 2.9

Basic Characteristics of the FB-Type Filters

(1) Тип фильтра	(2) Число проводов	(3) Номинальный рабочий ток, А	(4) Номинальное рабочее напряжение (фаза—корпус), В				(9) Диапазон частот, МГц, при затухании не менее 100 дБ	(10) Габаритные размеры, мм³	(11) Масса, кг
			постоянного тока (5)	50 Гц (6)	400 Гц (7)	1000 Гц (8)			
(12)ФБ-1	16	3	250	250	—	—	5...10 000	350×40×45	0,7
ФБ-1М	16	3	250	250	—	—	8...10 000	250×40×45	0,6
ФБ-2М	16	3	250	250	250	—	8...10 000	270×40×45	0,6
ФБ-2Т	16	0,1	60	60	60	60 до 3000	1...10 000	380×70×75	2,6
ФБ-3	4	50	250	250	250	250	1,5...10 000	340×100×100	5,0
ФБ-3М	4	50	250	250	250	250	3...10 000	300×100×100	4,0
ФБ-4	4	100	250	250	250	250	1,5...10 000	340×195×100	9,6
ФБ-4М	4	100	250	250	250	250	3...10 000	300×195×100	7,2
ФБ-5	4	25	250	250	250	250	10...10 000	325×45×45	1,3
ФБ-5М	4	25	250	250	250	250	20...10 000	260×45×45	1,0
ФБ-6	2	200	30	—	—	—	0,25...10 000	330×130×70	4,0
ФБ-6М	2	200	30	—	—	—	0,55...10 000	300×100×50	2,6
ФБ-7	2	50	250	250	250	250	1,5...10 000	340×100×50	3,0
ФБ-7М	2	50	250	250	250	250	3...10 000	300×100×50	2,4
ФБ-8	16	25	250	250	250	250	10...10 000	340×100×90	4,5
ФБ-8М	16	25	250	250	250	250	20...10 000	275×100×30	3,5

Key:

1. Type of filter
2. No of wires
3. Rated operating current, amps
4. Rated operating voltage (phase-housing), volts
5. Direct current
6. 50 hertz
7. 400 hertz
8. 1000 hertz
9. Frequency band, megahertz, with no less than 100 decibels of attenuation
10. Overall dimensions, mm^3
11. Mass, kg
12. FB...

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FB-Type Filters. The nomenclature includes 16 types of wide-band interference-suppressing low-frequency filters designed to attenuate radio frequency interference with an effectiveness of no less than 100 decibels in DC, pulsating and AC networks with voltages of 30 to 250 volts and operating loads of 0.1 to 200 amps [42].

With respect to the electric circuit diagram and the structural execution they are analogous to the FP filters (see Fig 2.14), but they are executed from elements with improved characteristics by advanced technology. In the majority of the FB filters the application of elements with distributed parameters permits these filters to operate effectively in frequency band to 10 gigahertz and higher. For example, for power cables the FB filters contain K72P-3, MBP capacitors and coilless chokes using compositional ferrite cores, which have low sensitivity to the powerful magnetizing currents. With small dimensions such chokes have stable high resistance in a wide frequency spectrum. In the weak-current filters of the given series, miniature ceramic duct elements of the B7-2 type are used.

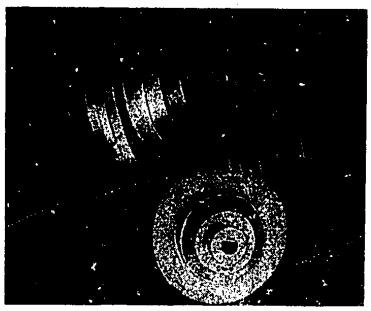

Figure 2.15. FPS-2 type filter

Table 2.10

Basic Characteristics of the FPS Type Filters

(1) Тип фильтра	(2) Число проводов	(3) Рабочий ток, А	(4) Рабочее напряжение („фаза—корпус"), В	(5) Вносимое затухание, дБ, в диапазоне частот, ГГц			(6) Габаритные размеры, мм³	(7) Масса, кг
				0,3...1	1...5	5...10		
(8) ФПС-1	1	10	250	60	80	100	14×94	0,1
ФПС-2	9	5	250	60	60	60	60×60	0,9
ФПС-3	1	50	500	40	60	80	60×32	0,7
ФПС-4	1	100	500	60	80	100	50×165	2,6
ФПС-5	4	50	500	20	40	60	85×225	5,6

Key: 1. Type of filter; 2. No of wires; 3. operating current, amps; 4. operating voltage (phase-housing), volts; 5. introduced damping, decibels, in the frequency band, gigahertz; 6. overall dimensions, mm^3; 7. mass, kg; 8. FPS ...

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It is also necessary to note that the majority of the FB series filters, as is obvious from Table 2.9, permit operation in AC circuits with increased industrial frequency.

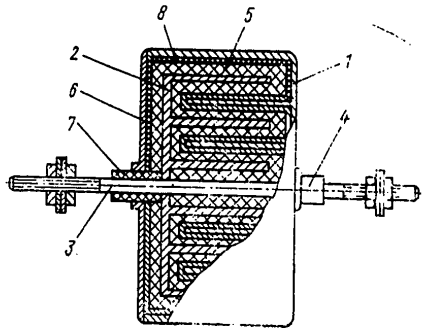

Figure 2.16. Structure and a general view of the FPS-3 filter: 1 -- case; 2 -- inside conductor; 3 -- current-conducting rod; 4 -- insulating washer; 5 -- absorber; 6 -- cover; 7 -- insulating washer

FPS-Type Filters. The nomenclature of the interference-suppressing microwave filters of the FPS type contains five types (Table 2.10). The FPS-1 filter is single-wire, П-type, low-frequency. It is made of two of the KTP-3 type capacitors with a capacitance of 15000 picofarads and a cylindrical absorber made of ferroexpoxy. The FPS-2 filter is a 9-wire filter made up of V7-2 ceramic elements (see Fig 2.15). The FPS-3, FPS-5 absorbing filters are of the greatest interest in the series [44, 45, 46] (Fig 2.16-2.18).

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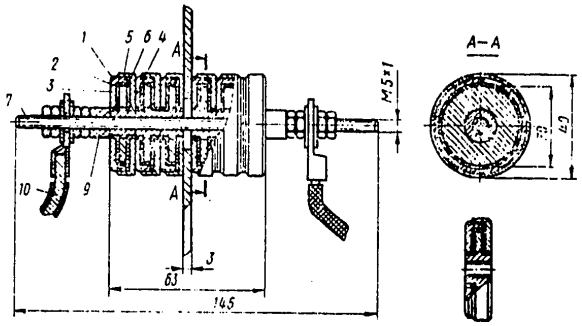

Figure 2.17. Structure and general view of the FPS-4 type filter:
1 -- brass cup; 2 -- insulating cup; 3 -- ring made of absorbing material; 4 -- bushing; 5 -- cover; 6 -- insulating insert; 7 -- current-conducting rod; 8 -- shield; 9 -- insulator; 10 -- power supply line

With respect to structural design the FPS-3 is a segment of a nonuniform coaxial line, the inside and outside conductors of which are made in the form of two metal rods entering into each other with a number of concentric walls, the space between which is filled with absorbing mass. The FPS-4 filter (Fig 2.17) is made up of a set of absorbing washers, each of which is formed by a short segment of the coaxial line with a layer of absorbing material. In assembled form the entire structure is a coaxial absorbing low-frequency filter with step shape of the outside conductor. The FPS-5 filter contains four parallel insulated current-conducting wires located closer to each other surrounded by a common absorber of microwave electromagnetic energy and a common external metallic shield of cylindrical shape.

All of the FPS series filters are distinguished by small dimensions, high mechanical and climatic characteristics, as a result of which they can be successfully used to protect the stationary and mobile equipment.

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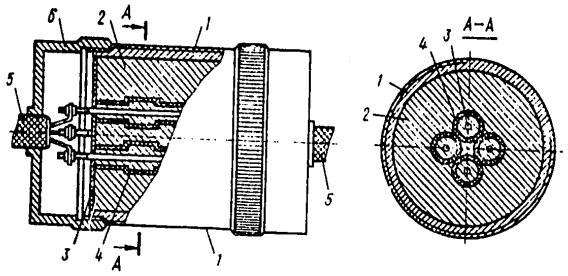

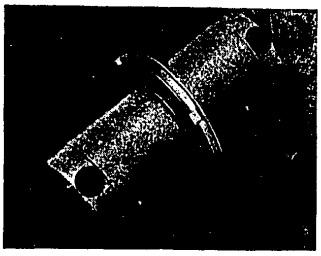

Figure 2.18. Structure and general view of the FPS-5 type filter:
1 -- brass housing; 2 -- absorber; 3 -- current-conducting line;
4 -- insulation; 5 -- power cable; 6 -- cap nut

2.9. Calculation of Shields and Experimental Data on the Shielding Effectiveness

The variety and random nature of the factors determining the shielding effectiveness significantly complicates the engineering calculation of the shields. However, in spite of the comparatively low accuracy of these calculations, as a rule, they turn out to be necessary for designing radio-electronic equipment.

Inasmuch as the basic characteristic of the shield is its effectiveness, the engineering calculation procedure must begin with the dependence of this characteristic on the wave length λ, the modulus of the wave impedance of the dielectric Z with respect to the type of wave, the shield material, on the parameters which determine the geometric dimensions of the shield and the quality of the structural design. It is highly complicated to obtain such relations by theoretical means alone. Therefore, usually we resort to processing and generalizing experimental data and constructing formulas on the basis of this to calculate the shielding effectiveness in a broad frequency range. It is necessary that the formulas be simple and give the required accuracy of coincidence of the calculated and experimental results. In the formulas consideration must be given to the characteristics

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of the materials and the structural design of the shields, the basic physical processes and the characteristic features of the shielding of the electromagnetic field components.

The most convenient both for the construction of the calculation formula itself and for its use is the expression of the effectiveness of the shielding by the product of a number of cofactors, each of which defines the effect of one of the factors or one group of similar factors.

As a result of analyzing any structural designs of shields for different purposes the author obtained expressions for the average shielding effectiveness:

$$\Theta_{0E(H)} = 0{,}024 \sqrt{\frac{\delta}{\rho} Z_{E(H)}} \sqrt[3]{\frac{\lambda}{R_э}} e^{\frac{2\pi d}{m}} \times \times \left(\frac{a-m}{m}\right)^2 \left(1 - \frac{\pi m}{\lambda}\right)^6, \quad (2.22)$$

where δ is the depth of penetration, meters; ρ is the specific resistance of the shield material, ohm-meter; $Z_{E(H)}$ is the wave impedance of the electric (magnetic) field; $R_э$ is the equivalent radius of the shield, m; a is the spacing between the centers of the openings and the slits in the shield occurring as a result of imperfection of its structural design and the manufacturing process, meters; m is the greatest size of the opening (slit) in the shield, meters; d is the thickness of the shield material, meters. It is obvious that $m>0$, a and m are random variables.

Analysis has shown that the average value of the cofactor $(m/(a-m))^2$ for the usual technological process and high quality of installation is close to 0.024. Therefore it is possible to represent expression (2.22) in the form

$$\Theta_{0E(H)} = \sqrt{\frac{\delta}{\rho} Z_{E(H)}} \sqrt[3]{\frac{\lambda}{R_э}} e^{\frac{2\pi d}{m}} \left(1 - \frac{\pi m}{\lambda}\right)^6. \quad (2.23)$$

This formula is the most general and fully characterizes the process of the electromagnetic shielding of real shields. It is necessary to note that in it the factor $e^{d/\delta}$ is missing which is present in expression (1.35) for the shielding effectiveness of an absolutely electrically sealed shield. This factor characterizes the attenuation of the field in the body of the shield when there are no other propagation paths for the electromagnetic energy, and this factor is much larger than the remaining cofactors with respect to magnitude. The slits and openings in the shield form additional energy emission paths, as a result of which its effectiveness decreases. Inasmuch as the effect of these additional paths is predominant in expressions (2.22) and (2.23), the effectiveness of the shield is characterized by the factor exp ($2\pi d/m$) in which the role of the thickness of the material and the size of the slit is uniquely expressed.

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The basic shielding factor in the real structural designs of radio-electronic equipment is reflection of the electromagnetic wave from the surface of the shield as a result of the difference of its surface resistance and the wave impedance of the field defined by the factor $\sqrt{(\delta/\rho)Z_{E(H)}}$.

Formula (2.23) is applicable for a wide range of wave length, while $\lambda>m\pi$. For $\lambda\to m\pi$ the factor $(1-m\pi/\lambda)^6$ decreases sharply, and the shielding effectiveness becomes insignificant. This factor determines the effectiveness of the shield caused by its seal.

For perforated materials when the dimension a and the hole diameter are perforation parameters, expression (2.23) is written as follows:

$$\vartheta_{0E;(H)}=\sqrt{\frac{\delta}{\rho}Z_{E(H)}}\sqrt[3]{\frac{\lambda}{R_\Box}}\left(\frac{a-D}{a}\right)^2\left(1-\frac{\pi m}{\lambda}\right)^6\exp\left(\frac{2\pi d}{m}\right). \tag{2.24}$$

Formula (2.24) is applicable for a>D and the existence of slits in the shield with $m<\lambda/\pi$ not connected with the size of the perforation opening. The factor $((a-D)/a)^2$, depending on the relation between a and D, can vary within limits from 1 to 0, but in practice it is always less than one and greater than zero. If the perforation parameters are such that the diameter of the opening D is greater than the random slit size, then D is substituted in place of m in $e^{2\pi d/m}$ and $(1-\pi m/\lambda)^6$, that is, these factors are written as $e^{2\pi d/D}$ and $(1-\pi D/\lambda)^6$. In the case where a>>D expressions (2.23) and (2.24) are identical.

For shields made of screen materials, the equivalent thickness of the screen $d_э=\pi r_s^2/s$ is taken as the thickness of the shield (p 49). The formula for calculating the effectiveness of such shields assumes the form

$$\vartheta_{oc}=\sqrt{\frac{d_э}{\rho}Z_E}\sqrt[3]{\frac{\lambda}{R_\Box}}e^{\frac{\pi d_s}{s-d_c}}\left(1-\frac{\pi m}{\lambda}\right)^6, \tag{2.25}$$

where $d_э$ is the equivalent thickness of the screen, meters; d_s is the screen wire diameter, mm; s is the screen spacing, mm.

The effectiveness of the shields made of electrically thin materials, including with metal-plated surfaces, is defined by the expression

$$\vartheta_0=1{,}25\pi\sqrt{\frac{d}{\rho}Z_E}\sqrt[3]{\frac{\lambda}{R_\Box}}\left(1-\frac{\pi m}{\lambda}\right)^6. \tag{2.26}$$

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The thickness of the applied layer of metal $d=P_{pm}/\gamma$ is taken as the thickness of the shield with the metal-plated surfaces, where P_{pm} is the metal consumption, kg/m^2; γ is the density of the initial material, kg/m^3.

Finally, the shielding effectiveness of current-conducting paint is calculated by the formula

$$\Theta_0 = 1{,}25\pi \sqrt{\frac{Z_E}{R_\square}} \sqrt[3]{\frac{\lambda}{R_э}} \left(1 - \frac{\pi m}{\lambda}\right)^6, \qquad (2.27)$$

where $R_\square$ is the resistance per square area of the shield surface, ohms. Let us some examples to illustrate the calculation sequence. Let it be required to estimate the shielding effectiveness of shields of identical size 2.0x1.5x1.0 m^3 made of various materials in the wave length range of $3\cdot10^3$ to $3\cdot10^{-1}$ meters.

The shield 1 is sheet steel 1.5 mm thick. The sheets are fastened to a metal frame by bolts with a spacing of the fastenings of 10 cm. With this type of fastening of the skin, as practice shows, the slits can be no more than 10 mm. The specific resistance of the steel $\rho=10^7$ ohm-meter. Let us determine the shielding effectiveness for a wave length of $\lambda=3\cdot10^3$ m.

The equivalent radius of the shield is determined from (1.39):

$$R_э = 0{,}62 \sqrt[3]{blh} = 0{,}62 \sqrt[3]{2\cdot1{,}5\cdot1} = 0{,}9 \text{ м}.$$

The wave impedance of the electric and magnetic fields is calculated by formulas (1.7) or using the graph in Fig 1.5. For $2\pi R_э/\lambda = 5{,}65/3\cdot10^3 \ll 1$ the wave impedance of the electric field

$$Z_E = \frac{Z_0\lambda}{2R_э\pi} = \frac{377\cdot3\cdot10^3}{6{,}28\cdot0{,}9} = 2\cdot10^5 \text{ ohms}.$$

We find the wave impedance of the magnetic field analogously:

$$Z_H = Z_0 \frac{2\pi R_э}{\lambda} = \frac{377\cdot6{,}28\cdot0{,}9}{3\cdot10^3} = 0{,}7 \text{ ohms}.$$

The depth of penetration according to (1.29) is

$$\delta = 0{,}03 \sqrt{\frac{\lambda\rho}{\mu_r}} = 0{,}03 \sqrt{\frac{3\cdot10^3\cdot10^{-7}}{180}} = 4\cdot10^{-5} \text{ м}.$$

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Let us find the values of the factors in expression (2.23):

$$\sqrt{\frac{\delta}{\rho}Z_E}=\sqrt{\frac{4\cdot10^{-6}}{10^{-7}}2\cdot10^{5}}=0{,}9\cdot10^{4},$$

$$\sqrt[3]{\frac{\lambda}{R_э}}=\sqrt[3]{\frac{3\cdot10^{2}}{0{,}9}}=15,$$

$$e^{2\pi d/m}=e^{6{,}28\cdot1{,}5/10}=2{,}6,$$

$$\sqrt{\frac{\delta}{\rho}Z_H}=\sqrt{\frac{4\cdot10^{5}}{10^{-7}}\cdot0{,}7}=17{,}0,$$

$$\left(1-\frac{\pi m}{\lambda}\right)^{6}=\left(1-\frac{3{,}14\cdot10^{-2}}{3\cdot10^{2}}\right)^{6}\approx1.$$

The shielding effectiveness of the electric field

$$\Theta_{0E}=\sqrt{\frac{\delta}{\rho}Z_E}\sqrt[3]{\frac{\lambda}{R_э}}e^{\frac{2\pi d}{m}}\left(1-\frac{\pi m}{\lambda}\right)^{6}=0{,}9\cdot10^{4}\cdot15\cdot2{,}6=$$
$$=3{,}5\cdot10^{5}\text{ or }111\text{ decibels.}$$

Correspondingly, for a magnetic field we obtain

$$\Theta_{0H}=\sqrt{\frac{\delta}{\rho}Z_H}\sqrt{\frac{\lambda}{R_э}}e^{\frac{2\pi l}{m}}\left(1-\frac{\pi m}{\lambda}\right)^{6}=17\cdot15\cdot2{,}6=660\text{ or }57\text{ decibels.}$$

The shielding effectiveness is calculated analogously for other points of the operating wave length band. The results of the calculations and the measurements for the shield 1 are presented in Table 2.11.

Shielding 2 is made up of aluminum sheets 1.5 mm thick. The structure is the same as that for shield 1. The specific resistance of the aluminum $\rho=2.8\cdot10^{-8}$ ohms-meter. Let us calculate the shielding effectiveness for $\lambda=3\cdot10^{2}$ meters.

The wave impedance of the electric field

$$Z_E=\frac{Z_0\lambda}{2\pi R_э}=\frac{377\cdot3\cdot10^{2}}{6{,}28\cdot0{,}9}=2\cdot10^{4}\text{ ohms,}$$

of the magnetic field

$$Z_H=\frac{2\pi R_э}{\lambda}Z_0=\frac{377\cdot6{,}28\cdot0{,}9}{3\cdot10^{2}}=7\text{ ohms.}$$

The depth of penetration is

$$\delta=0{,}03\sqrt{\rho\lambda}=0{,}03\sqrt{2{,}8\cdot10^{-8}\cdot3\cdot10^{2}}=8{,}7\cdot10^{-4}\text{ м.}$$

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The values of factors are:

$$\sqrt{\frac{\delta}{\rho} Z_E} = \sqrt{\frac{8{,}7\cdot 10^{-8}}{2{,}8\cdot 16^{-8}} 2\cdot 10^{4}} = 0{,}8\cdot 10^{4},$$

$$\sqrt{\frac{\delta}{\rho} Z_H} = \sqrt{\frac{8{,}7\cdot 16^{-8}}{2{,}8\cdot 16^{-8}}\cdot 7} = 1{,}5\cdot 10^{3},$$

$$\sqrt[3]{\frac{\lambda}{R_э}} = \sqrt[3]{\frac{3\cdot 10^{2}}{0{,}9}} = 7{,}0, \qquad e^{\frac{2\pi l}{m}} = e^{6{,}28\cdot 1{,}5/10} \approx 2{,}6.$$

The shielding effectiveness of the electric component of the field is

$$э_{0E} = \sqrt{\frac{\delta}{\rho} Z_E}\sqrt[3]{\frac{\lambda}{R_э}} e^{\frac{2\pi l}{m}} \left(1-\frac{\pi m}{\lambda}\right)^{6} = 0{,}8\cdot 10^{4}\cdot 7\cdot 2{,}6 =$$
$$= 1{,}45\cdot 10^{5} \text{ or } 103 \text{ decibels.}$$

The shielding effectiveness of the magnetic component of the field is

$$э_{0H} = \sqrt{\frac{\delta}{\rho} Z_H}\sqrt[3]{\frac{\lambda}{R_э}} e^{\frac{2\pi l}{m}} \left(1-\frac{\pi m}{\lambda}\right)^{6} = 1{,}5\cdot 10^{3}\cdot 7\cdot 2{,}6 =$$
$$= 2{,}7\cdot 10^{3} \text{ or } 68 \text{ decibels.}$$

The shielding effectiveness for other points of the operating wave length band calculated analogously and the measurement data are presented in Table 2.11. From the table data it is obvious that the results of the calculations and the measurements in practice coincide. With a decrease in wave length, beginning with $\lambda = \pi R_э \approx 3$ м, the shielding effectivenesses of the field components become equal, which indicates the establishment under these conditions of the electromagnetic process in the shield. The comparatively fast decrease of the effectiveness as λ decreases is explained by the more intense effect of the slits.

The shield 3 is made of a brass screen with spacing s=0.25 mm, r_s=0.045 mm. The screen is stretched on a wooden frame. The webbing of the screen is soldered along the entire length. Slits no longer than 6 to 7 mm can occur in the contact system of the door opening and at the points of connecting the screens. Let us determine the effectiveness for λ=30 m, $\rho = 7.5\cdot 10^{-8}$ ohm-meter.

The equivalent thickness of the shield material will be

$$d_э = \frac{\pi r_s^2}{s} = \frac{\pi (0{,}045\cdot 10^{-3})^2}{0{,}25\cdot 10^{-3}} \approx 2{,}5\cdot 10^{-4} \text{ м.}$$

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Table 2.11

Shielding Effectiveness of Shields Made of Different Materials, Decibels

λ, м	(1) Экран 1			(2) Экран 2			Экран 3 (3)			Экран 4 (4)			Экран 5 (5)		
	$э_H$	$э_E$	$э_{Елзм}$(6)	$э_H$	$э_E$	$э_{Елзм}$(6)	$э_E$	$э_{Елзм}$(6)		$э_E$	$э_{Елзм}$(6)		$э_E$	$э_{Елзм}$(6)	
$3 \cdot 10^3$	57	111	—	70	125	—	1	—		107	—		120	—	
$3 \cdot 10^2$	56	88	89	68	103	100	101	—		91	94		106	106	
$3 \cdot 10^1$	54	68	67	65	88	86	85	86		74	73		90	93	
$3 \cdot 10^0$	49	48	46	60	60	60	67	65		59	58		76	81	
$3 \cdot 10^{-1}$	33	33	31	39	39	39	58	56		50	48		70	72	

Key:
1. Shield 1
2. Shield 2
3. Shield 3
4. Shield 4
5. Shield 5
6. measured

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The wave impedance of the electric component will be found by the graph in Fig 1.5. For $2\pi R_0/\lambda=6{,}28\cdot0{,}9/30=0{,}19$, we obtain $Z_E/Z_0=5$, hence $Z_E=377\cdot6=1900$ ohms.

The values of the factors in expression (2.25) are as follows:

$$\sqrt{\frac{\delta}{\rho}Z_E}=\sqrt{\frac{25\cdot10^{-6}}{7{,}5\cdot10^{-8}}\,1{,}9\cdot10^{3}}=8\cdot10^{2}$$

$$\sqrt[3]{\frac{\lambda}{R_s}}=\sqrt[3]{\frac{30}{0{,}9^{*}}}=3{,}2,$$

$$\exp(\pi d_*/s-d_*)=\exp(3{,}14\cdot0{,}09/0{,}25-0{,}09)=5{,}8.$$

The shielding effectiveness will be $\Theta_{0\Sigma}=8\cdot10^{2}\cdot3{,}2\cdot5{,}8=1{,}5\cdot10^{4}$ or 85 decibels.

The results of the calculations and the measurements for other points of the operating wave band are presented in Table 2.11.

Shield 4 is identical to shield 3. The screen parameters are as follows: steel, spacing s=1 mm, wire radius r_s=0.125 mm (see Table 2.11).

Shield 5. The supporting base is a plywood chamber, the inside surface of which is coated with aluminum foil 0.08 mm thick. The foil sheets are glued with silicate glue with 50 mm overlap. The glue is applied only to an overlap strip 15 mm wide. Let us propose that on the remaining 35 mm of width of overlap, a reliable electric contact is created. Actually in many sections the electrical contact will be absent, but there will be no through slits.

The calculation data using formula (2.26) and the results of the measurements are presented in Table 2.11.

The shield 6 -- the supporting base -- is a plywood chamber, the inside surface of which is coated with current-conducting paint with surface impedance $R_\square$ =6 ohms.

The calculation of the shielding effectiveness is made by formula (2.27). The calculations show that on a frequency f=0.15 megahertz the effectiveness is equal to 77 decibels, and on a frequency f=1000 megahertz, Θ_Σ=32 decibels, which in practice coincides with the measurement data.

The shield 7 is made of sheet aluminum 1.5 mm thick. The rear upper and lower walls are perforated, a=15 mm, D=10 mm. The fastening of the skin sheets is just as in shield 1. The large dimension of the slit is equal to the perforation diameter.

Let us define the effectiveness of the shielding on a wave of λ=3.0 meters. Let us determine the wave impedances of the field components by the graph in Fig 1.5. For $2\pi R_0/\lambda=1{,}9$ we have Z_E=300 ohms and Z_H=350 ohms.

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The values of the factors in expression (2.24) are:

$$\sqrt{\frac{\delta}{\rho} Z_E} = \sqrt{\frac{9 \cdot 10^{-6}}{2{,}8 \cdot 10^{-8}} 3 \cdot 10^2} = 3 \cdot 10^2,$$

$$\sqrt{\frac{\delta}{\rho} Z_H} = \sqrt{\frac{9 \cdot 10^{-6}}{2{,}8 \cdot 10^{-6}} 350} = 3{,}3 \cdot 10^2.$$

$$\exp\left(\frac{2\pi l}{D}\right) = \exp\left(\frac{6{,}28 \cdot 1{,}5}{10}\right) = 2{,}6, \quad \sqrt[3]{\frac{\lambda}{R_9}} = \sqrt[3]{\frac{3}{0{,}9}} = 1{,}5,$$

$$\left(\frac{a-D}{a}\right)^2 = \left(\frac{15-10}{15}\right)^2 = \frac{1}{9},$$

$$\left(1 - \frac{\pi D}{\lambda}\right)^6 = \left(1 - \frac{\pi 10 \cdot 10^{-3}}{3}\right)^6 \approx 0{,}86.$$

The shielding effectiveness will be correspondingly

$$\vartheta_{0E} = \sqrt{\frac{\delta}{\rho} Z_E} \sqrt[3]{\frac{\lambda}{R_9}} e^{2\pi l/D} \left(\frac{a-D}{a}\right)^2 \left(1 - \frac{\pi D}{\lambda}\right)^2 =$$

$$= 3 \cdot 10^2 \cdot 1{,}5 \cdot \frac{1}{9} 2{,}6 \cdot 0{,}86 = 1{,}1 \cdot 10^2 \text{ or } 41 \text{ decibels},$$

$$\vartheta_{0H} = 3{,}3 \cdot 10^2 \cdot 1{,}5 \frac{1}{9} 2{,}6 \cdot 0{,}86 \approx 1{,}2 \cdot 10^2 \text{ or } 41 \text{ decibels}.$$

A comparison of the results of the calculations with the measurement data and analysis of the factors entering into expressions (2.23) to (2.27) make it possible to draw the following conclusions.

1. The formulas obtained as a result of the experiment provide for sufficiently accurate calculation of the effectiveness of the shields of different designs for practice.

2. As a result of the impossibility with modern installation technology of insuring high electric seal of the shields, their effectiveness remains comparatively low at high frequencies. It is inexpedient to use expensive highly effective materials in the shields, for their shielding properties are only partially used.

3. As the disturbances of the seal increase, the effectiveness of the shields made of the materials with high and low shielding properties become identical. This phenomenon is especially characteristic for the high-frequency range.

4. For disturbances of the electric seal a significant role is played by the thickness of the material, with an increase in which it is possible partially to compensate for a decrease in the shielding effectiveness.

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Table 2.12

Shielding Effectiveness of the Structures of Closed Shields, Decibels

Material, shielded device and structure of the shield	Frequency band, megahertz				
	0.5-3	3-30	30-300	300-3000	300-10000
Sheet steel:					
welding in a continuous weld	100	100	100	100	100
spot welding, spacing 50 mm	70	50	-	-	-
sheets fastened with bolts, spacing 50 mm	75	60	-	-	-
Tin plate (by a seam):					
continuous solder	100	100	100	100	100
spot solder, spacing 50 mm	100	80	60	50	40
without solder	100	100	60	50	40
Metal screen:					
solder, mesh 1 to 1.5 mm	80	60	50	40	25
Foil:					
dovetail glueing (overlap seam)	100	80	80	70	60
Current-conducting seam (R_D=6 ohms)	70	40	30	40	40
Metal plating:					
metal consumption 0.3 kg/m^2	100	80	60	50	40
Shielding of the inspection holes and windows:					
of the flap or door made of metal screen with 1 to 1.5 mm mesh	70	60	60	40	40
welded steel sheet or soldered tin plate	100	100	80	80	70
honeycomb lattice	100	100	100	-	-
metal screen with mesh up to 2 mm	70	60	40	20	-
glass with conducting surface	70	30	-	30	30
Shielding of the door openings:					
single door on the frame, covered by steel sheet, solid adjustable contact	80	70	70	60	60
the same, but brush contact with spacing of 100 mm	70	60	40	30	30
open, limiting wave guide	100	60	-	-	-

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Table 2.12 [continued]

Material, shielded device and structure of the shield	Frequency band, megahertz				
	0.5–3	3–30	30–300	300–3000	300–10000
attached cover with double contact and clamp	100	100	80	60	60
double door with entry space, solid adjustable contact or pneumatic	100	100	100	100	100
Shielding of channels:					
open, limiting wave guide	100	100	100	100	100
honeycomb lattice	100	100	100	100	100
metal screen with 5 mm mesh	70	60	30	-	-
perforated insert	70	60	40	-	-
Shielding of the communication line lead ends:					
metal tubes soldered to the shield around the entire perimeter	100	100	100	100	100
metal tubes made in the wave guide connecting lines	100	100	100	100	100
filters with the corresponding effectiveness	100	100	100	100	100

Note. The presented numerical data pertain to the upper boundary of the subrange and to the time of manufacturing the shields.

The experience in the design, manufacture, testing, operation and maintenance of the shielding structures and systems indicates that on the average the shielding effectiveness of the equipment and the installations can be achieved on the level of the data presented in Table 2.12. These data pertain to the upper frequency limit of the subband. The overall effectiveness is determined by the low value of the effectiveness of one of the shield nodes itself. The absence in Table 2.12 of digital values for the individual devices means that the investigated version is not recommended or is unrealizable.

The data in Table 2.12 simplify the choice of the basic nodes of the screen and its design as a whole, for the volume of calculations is reduced.

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CHAPTER 3. SHIELDING OF THE ASSEMBLIES AND MODULES OF RADIO-ELECTRONIC EQUIPMENT

3.1. Coils, Filters and Transformers

The shielding of the inductive coils is realized using closed metal shields of cylindrical or rectangular shape made of nonmagnetic materials such as copper, brass and aluminum.

For the oscillatory circuits of the end-type stages of the powerful transmitting devices, predominantly medium long wave, long wave and the low-frequency part of the medium wave and short wave bands, shielded facilities are used in the required cases.

When designing the coil shield it is necessary to solve one of two problems:

By the given measurements of the coil frame ($D_k \ell_k$) and the initial inductance L_0, determine the shield diameter $D_э$ (or the length of side b of square cross section) and its length $\ell_э$ (Fig 3.1);

By the given dimensions of the shield $D_э$, $l_э$ and the initial inductance L_0, determine the diameter of the coil frame D_k, its length ℓ_k and the winding pitch.

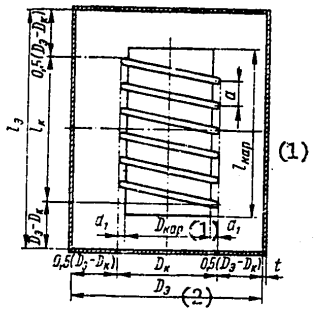

Figure 3.1. Coil in the cylindrical shield

Key:
1. Frame; 2. shield

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In both problems the number of turns N and the wire diameter d_{wire} are also determined.

The solution of the problems is based on calculating the reaction of the shield to the shielded coil and the increase in losses in it as a result of the eddy currents absorbing part of the oscillatory energy. The shield dimensions are determined beginning with the fact that the initial coil inductance can be decreased by no more than 5 to 20% or that the losses must not exceed 0.5 to 1.0% of the oscillatory power. Usually this is achieved by the corresponding selection of the shield material and the ratio $D_к/D_э=0{,}45 \ldots 0{,}6$. For stationary conditions of the powerful oscillatory circuit more frequently we set $D_к/D_э<0{,}45$.

In order that the winding be at the same distance from the side and the end walls of the shield, the following are selected:

For the cylindrical shield

$$D_э-D_к=l_э-l_к, \qquad (3.1)$$

For the rectangular shield with square cross section

$$1{,}2b-D_к=l_э-l_к. \qquad (3.2)$$

Then for the given D_k/D_{shield} we find D_{shield}, and from (3.1) the length ℓ_{shield}.

The inductance of the single-wire coil L_0 decreases on placement of it in the shield, and it can be defined by one of the formulas:

$$L_э=L_0\beta_L, \qquad L_э=L_0-|\Delta L|, \qquad (3.3)$$

where ΔL is the increment of the inductance; $\Delta L<0$; β_L is the coefficient of the variation of the inductance determined by the approximate formula [18]

$$\beta_L \approx \left[1-\left(\frac{D_к}{D_э}\right)^2\right]\left[1-\left(\frac{l_к}{2l_э}\right)^2\right]. \qquad (3.3')$$

From formulas (3.3) it follows that the relative decrease in the inductance will be

$$\frac{|\Delta L|}{L_0}=\left(\frac{l_к}{2l_э}\right)^2+\left(\frac{D_к}{D_э}\right)^2\left[1-\left(\frac{l_к}{2l_э}\right)^2\right]. \qquad (3.4)$$

Since the Q-factor of the coil without the shield $Q_0=\omega L_0/R_0$, the increment in the Q-factor as a result of variation of L_0, R_0 will be

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$$\Delta Q = Q_0\left(\frac{\Delta L}{L_0} - \frac{\Delta R}{R_0}\right), \qquad (3.5)$$

where $\Delta L/L_0$ is the relative variation of inductance; $\Delta R/R_0$ is the relative variation of the active resistance.

The active resistance introduced by the shield into the equivalent circuit of the inductance coil considering the surface effect, as is illustrated in [14], is

$$\Delta R = \frac{3}{2}\frac{N^2\pi}{\sigma\delta}\left(\frac{D_к}{D_э}\right)^4, \qquad (3.6)$$

for the low-frequency zone where the surface effect can be neglected

$$\underset{(1)}{\Delta R_{нч}} = \frac{3}{2}\frac{N^2}{\sigma d}\left(\frac{D_к}{D_э}\right)^4, \qquad (3.7)$$

Key: 1. low frequency

where $D_э$ is the diameter of the shield of cylindrical shape or the equivalent diameter of a shield of rectangular shape; d is the shield thickness, cm; σ is the electrical conductivity of the shield material $(\text{ohm-cm})^{-1}$; δ is the depth of penetration, cm; N is the number of coil turns.

The resistance of the single-layer coil without the shield wound with wire d_1 diameter under the condition that $10^2 d_1\sqrt{f} > 5$ [47],

$$R_f = \frac{0{,}525 D_к N\sqrt{f}}{d_1}\,10^{-8}\ \text{Ом}, \qquad (3.8)$$

where f is the frequency, megahertz; D_k is the coil diameter, cm; d_1 is the diameter of the copper wire, cm.

Then the relative variation of the active resistance in the presence of the shield is

$$\frac{\Delta R}{R_f} = 2{,}3 N d_1 \frac{D_к^4}{D_э^4}. \qquad (3.9)$$

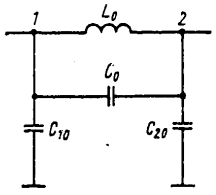

Figure 3.2. Equivalent diagram of the shielded coil

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In the presence near the coil of a grounded shield, the capacitance with respect to ground (the shield) is added to its natural capacitance C_0. These capacitances can be considered concentrated at the ends of the coil [13] (the capacitances C_{10}, C_{20} in Fig 3.2). For the ungrounded winding the coil capacitance

$$C_{06}=C_0+C_{10}C_{20}/(C_{10}+C_{20}). \quad (1)$$

Key: 1. winding

Assuming that $C_{10}\approx C_{20}$, we obtain $C_{winding}=C_0+C_{10}/2$.

If one of the ends of the coil is connected to the shield, the capacitance C_{20} turns out to be short-circuited and the overall capacitance will be $C'_{winding}=C_0+C_{10}$.

Thus, the natural capacitance of the coil in the shield depends on its circuit diagram and, as is obvious from Fig 3.2, on connection with one end of the coil to the shield, the total capacitance, $C_{winding}$ will increase by approximately $C_{10}/2$ or $C_{20}/2$ depending on which of these capacitances is smaller.

Example. Let a single-layer coil with diameter $D_k=5$ cm and length $\ell_k=3.5$ cm contain N=30 turns of copper wire 0.1 cm and let it be included in the closed cylindrical shield made of copper 0.1 cm thick. The probable size of the long side of the slit does not exceed 0.4 cm.

Let us define the relative variation of the coil parameters, the dimensions and the effectiveness of the shield on a frequency of f=1 megahertz.

First let us be given the ratio $D_к/D_э=0{,}5$. Let us find the shield diameter $D_{shield}=D_k/0.5=5/0.5=10$ cm and its length

$$l_э=D_э-D_к+l_к=10-5+3{,}5=8{,}5 \text{ см}.$$

The relative variation of the coil inductance will be

$$\frac{|\Delta L|}{L_0}=\left(\frac{l_к}{2l_э}\right)^2\left[1-\left(\frac{l_к}{2l_э}\right)^2\right]\left(\frac{D_к}{D_э}\right)^3=$$
$$=\left(\frac{3{,}5}{2\cdot 8{,}5}\right)^2\left[1-\left(\frac{3{,}5}{2\cdot 8{,}5}\right)^2\right]\left(\frac{5}{10}\right)^3\approx 0{,}16,$$

that is, the coil inductance in the shield decreases by 16%. The relative variation of the active resistance

$$\frac{\Delta R}{R_f}=2{,}3Nd\frac{D_к^3}{D_э^4}=2{,}3\cdot 30\cdot 0{,}1\frac{125}{10^4}\approx 0{,}086,$$

that is, the resistance increases by 8.6%.

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The Q-factor of the coil diminishes by 7.4%, for $\Delta Q/Q_0=\Delta L/L_0-\Delta R/R_f=0.16-0.086=0.074$.

Setting the equivalent radius of the shield $R_э$ =5 cm for $\lambda=3\cdot10^4$ cm, we find the wave impedance of the field components:

$$Z_E=\frac{\lambda Z_0}{2\pi R_э}=\frac{377\cdot10^4\cdot3}{2\pi\cdot5}\approx36\cdot10^4 \text{ ohms},$$

$$Z_H=Z_0\frac{2\pi R_э}{\lambda}=\frac{377\cdot2\pi\cdot5}{3\cdot10^4}\approx0,4 \text{ ohms}.$$

Now for $\rho=1.7.10^{-6}$ ohm-cm and $\delta=0.0067$ cm it is possible to determine the shielding effectiveness of the electric component of the field

$$э_{0E}=\sqrt{\frac{\delta}{\rho}Z_E}\sqrt[3]{\frac{\lambda}{R_э}}e^{\frac{2\pi d}{m}}\left(1-\frac{\pi m}{\lambda}\right)^6=$$

$$=\sqrt{\frac{0,0067}{1,7\cdot10^{-6}}36\cdot10^4}\sqrt[3]{\frac{3\cdot10^4}{5}}e^{\frac{2\pi\cdot0,1}{0,4}}=3,2\cdot10^6 \text{ or } 130 \text{ decibels},$$

and the magnetic component

$$э_{0H}=\sqrt{\frac{\delta}{\rho}Z_H}\sqrt[3]{\frac{\lambda}{R_э}}e^{\frac{2\pi d}{m}}\left(1-\frac{\pi m}{\lambda}\right)^6=$$

$$=\sqrt{\frac{0,0067}{1,7\cdot10^{-6}}\cdot0,4}\sqrt[3]{\frac{3\cdot10^4}{5}}e^{\frac{2\pi\cdot0,1}{0,4}}=3,4\cdot10^3 \text{ or } 71 \text{ decibels}.$$

The shielding effectiveness of the coils can become significantly worse if the input or output conductors are not shielded. The conductor shield must on the one hand be soldered to the coil shield and on the other to the shield of the output device.

If by the operating and maintenance conditions it is necessary to have access to the coil, then openings can be made in the shield in the form of wave guide tubes. The shield can also be made of a perforated material or open at the ends. In the latter case the total length increases: $l_{shield}=l_k+8D_{shield}$. It is possible to decrease the overall length by applying wave guide filters of the honeycomb type on the ends. In some cases only one end can be left open. It is possible to fasten the honeycomb lattice or cover by screws or by electrically conducting glue. Most frequently the shield is in the form of a cylinder which is open at the end where the edging is done to fasten it to the frame.

It is more technological to make the shields for the large size coils rectangular (square cross section). A butt joint is made dovetailed or using an angle iron.

The shield cover is attached so as to insure reliable electrical contact around the entire perimeter of the housing. The bottom part of the shield usually is made up of the frame to which it is attached.

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The problems of shielding low-frequency and powerful transformers, the installation of their filtering cells are discussed in detail in [48]. The structure and installation of the interference-suppressing filters were investigated in §2.8.

3.2. Measuring Circuits and Instruments

The necessity for shielding measuring circuits and instruments arises from the fact that these devices, being under the effect of intense electromagnetic fields, can lead to false representation of the state of the equipment or not insure the required measurement accuracy. In addition, localization of the field within the limits of the given volume, improper installation of the measuring instrument in the housing (shield) of the radio-electronic equipment disturbs its electric field and, consequently, lowers the shielding effectiveness.

The shielding of the measuring circuits as a whole and their elements is investigated in many papers, in particular in [49, 50]; therefore we shall limit ourselves here to a discussion of only the basic recommendations with respect to installing the measuring instrument in the radio-electronic equipment pertaining to its shielding.

Every measuring or display device installed on the basic shield of the equipment with a scale lead or other device for reading and display on the outside surface must have an additional shield. This shield can be a metal hood which covers the instrument and the opening for installing it from the inside surface of the bay (see Fig 3.3). The wiring for the display and measuring circuits approaching the instrument must be filtered and shielded. Their shielding sheathings must have reliable electric contact with the additional shielding and the housing of the transmitter.

Theoretically, any structural design is possible which does not disturb the electric seal of the general shielding. It is permissible to install the instruments on a special panel on the outside of the bay or module.

The shield of the measuring instrument is welded or fastened by bolts to the common shield; the points at which the shields are joined must be carefully cleaned.

When installing the measuring instrument inside the transmitter bay, it is possible to limit the shielding to the face panel.

The DC and low-frequency measuring instruments installed outside the bay usually are not shielded, but they are connected by shielded wires. The metal braiding of the wires is connected to grounded terminals of the instruments and the case (the shield) of the radio-electronic equipment at the points closest to the instruments. In addition, the measuring instrument circuits include blocked duct capacitors (see Fig 3.3.).

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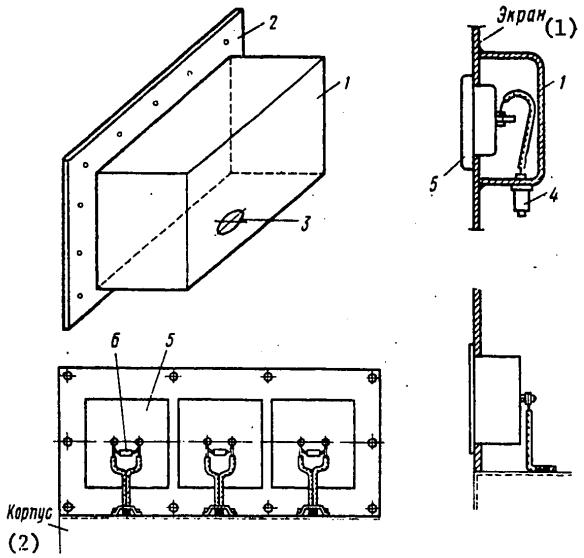

Figure 3.3. Shielding of the measuring instruments:
1 -- instrument shield; 2 -- flange; 3 -- opening for wires;
4 -- duct capacitor; 5 -- measuring instrument; 6 -- blocking capacitor

Key:
1. shield
2. housing

Sometimes it is expedient to locate the measuring instrument outside the shields of the high-frequency channels of the radio-electronic equipment but in this case the internal installation of the measuring circuits must be by shielding wiring. At the points where these circuits pass through the basic shield of the module, they must be filtered if necessary, and their shielding shells are connected electrically to the housing around the entire perimeter of the cross section of each wire or cable of the conductors.

3.3. Antenna Feeders

The structural design of an antenna feeder is made up of two basic elements: the antenna and the feeder.

When developing an electromagnetic shielding system for antenna feeders, it is also necessary to solve two problems.

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The first consists in selecting the location of the antenna system for which the interference emf induced in it will be minimal and not penetrate into the equipment. The solution of this problem is aimed at the attenuation of the influence on the effectiveness of the radio-electronic equipment shielding of its placement near the interference-carrying networks. In addition, in a number of cases it is necessary to establish the requirements also on the shielding of such networks.

The second problem pertains directly to the electromagnetic shielding equipment and consists in decreasing the antenna effect of the feeders using the shields.

In Fig 3.4 it is demonstrated how the interference penetrates through the inductive and capacitive couplings to the antenna or to the ground wire (when the emitter antenna is at a distance of $r \lesssim \lambda/2\pi$). Most frequently the interference in the receiving antenna decreases as is illustrated in Fig 3.4, a. If an interference current is passing through a conductor, the role of which can be played by any of the structural elements of the radio-electronic equipment, its field arises in the surrounding space. The interference emf in the receiving antenna can be determined by formula (1.8), where r is the minimum distance from the antenna to the interference-bearing wire, and U_π is the effective value of the interference voltage on the terminals of the external circuit of the receiver. In the particular case this can be splitting of the electric feed cable. It is possible to attenuate the interference effect by shielding the cable, filtering it and maximum removal of it from the receiving antenna.

The interference can reach the receiver through the capacitive coupling C_{coupling} between the conductor under the interference voltage $U_{\text{asymmetric interference voltage}}$ with respect to the ground, the antenna or its downlead. The path of the interference currents is illustrated in the equivalent diagram (see Fig 3.4, b), where C_a is the antenna-ground capacitance, Z_{input} is the resistance of the input circuit of the receiver. The same case is illustrated in Fig 3.5, where A and П are the points of connection of the antenna and the interference-bearing conductor to the receiver. The interference emf in the antenna [15] is

$$E_a = \underset{(1)}{U_{\text{инс}}} \frac{\ln b/a}{\underset{(2)}{\ln (4h_{\text{пр}}/D_a)}} \approx \underset{(3)}{U_{\text{инс}} h_a h_{\text{пр}}} \Big/ \left(\frac{l_a}{l_{\text{пр}}} L_r^2 \lg \frac{4h_{\text{пр}}}{D_a}\right), \quad (3.10)$$

Key: 1. asymmetric interference voltage; 2. conductor; 3. antenna

where $U_{\text{asymmetric interference voltage}}$ is the effective value of the asymmetric interference voltage in the conductor; l_a is the antenna length; $l_{\text{conductor}}$ is the length of the part of the antenna (the interference-bearing conductor) which is parallel to the interference-bearing conductor (the antenna); L_r is the horizontal distance between the antenna and conductor; D_a is the diameter of the antenna conductor.

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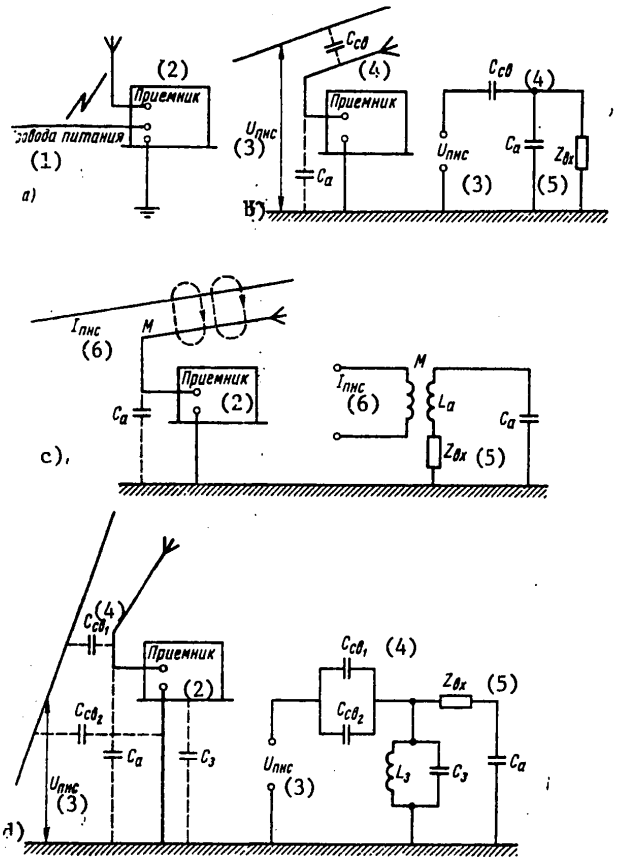

Figure 3.4. Effective interference on a radio receiver

Key:

1. Feed wires
2. Receiver
3. $U_{asymmetric\ interference\ voltage}$
4. $C_{coupling\ capacitance}$
5. Z_{input}
6. $I_{asymmetric\ interference\ current}$

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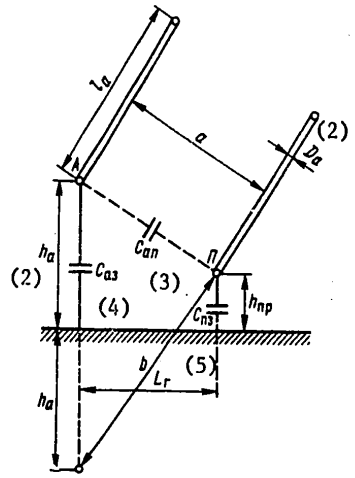

Figure 3.5. Partial capacitances between the antenna and a conductor near the ground

Key:
1. $h_{conductor}$
2. $D_{antenna}$
3. $C_{antenna-conductor}$
4. $C_{antenna-ground}$
5. $C_{conductor-ground}$

Here it is assumed that the diameters of the interference-bearing conductor and the antenna conductor are identical, the antenna and the interference-bearing conductors are not parallel along their entire length, and they are also conducted by the antenna-ground capacitance ($C_{antenna-ground}$), the conductor-ground capacitance $C_{conductor-ground}$ and the antenna-conductor capacitance ($C_{antenna-conductor}$).

With inductive coupling of the antenna to the interference-bearing conductor (see Fig 3.4, c) the interference emf can also be defined by the formula (3.10). Setting in it $U_{asymmetric\ interference\ voltage} = I_{asymmetric\ interference\ current}\rho_{conductor}$ where $I_{asymmetric\ interference\ current}$ is the asymmetric interference current; $\rho_{conductor}$ is the wave impedance of the interference-bearing conductor. Considering that for a single wire above the ground surface [51]

$$\underset{(1)}{\rho_{np}} = 138 \lg \underset{(2)}{(4h_{np}/D_a)},$$

Key: 1. conductor; 2. antenna.

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we find

$$E_a = 138 I_{нас} h_a h_{пр} \Big/ \frac{l_a}{l_{пр}} L_r^2. \qquad (3.11)$$

For the inductive coupling, a decrease in the interference emf induced in the antenna is also achieved by spacing the antenna and the conductor, shielding it and, in addition, by the exclusion or maximum reduction of the part of the conductor parallel to the antenna.

Fig 3.4, d shows how the interference can reach the input of the receiver as a result of the couplings between the receiver housing (with the grounding conductor connected to it) and the interference-bearing conductor through the coupling capacitances $C_{coupling\ 1}$ and $C_{coupling\ 2}$, parallel branching consisting of the inductance of the ground conductor L_{ground} and the housing capacitance with respect to ground $C_{housing}$. The interference currents flowing through the $L_{ground}C_{ground}$ circuit create a voltage drop on it and the equivalent interference emf in the circuit consisting of the input impedance of the receiver and the antenna-ground capacitance C_a.

In the presented examples the interference emf in the antenna circuit is caused by the asymmetric components of the currents and voltage in the interference-carrying network. Even under the condition of equality of the symmetric components in the interference-bearing network with asymmetric components, the symmetric components create interference voltages in the antenna network which are an order or more less. Consequently, along with the other measures of suppressing interference, symmetrizing the conductors of the two-wire interference-carrying network with respect to the ground and the antenna is effective.

The structural design and the placement of the antenna system have a strong influence on the overall noiseproofness of the receivers. In order to create improved reception conditions it is necessary to protect the largest possible space surrounding the antenna from the effects of the interference fields. The active parts of the antenna must be placed where there are no overhead electric power transmission lines, at the highest part of the device, and in the direction from the crossings or nodal connections of the electric power cables, signal and communication lines, and so on. The shielding of the cable of the antenna downlead must be electrically connected to the metal roof of the enclosure, module or building. The roofing sheets must be electrically connected at least in the sections which surround the active part of the antenna. The cable joining the antenna to the input of the receiver must be run along the shortest path. This cable must be laid in a special channel far from the lighting networks and the power plants. The continuity of the shield must not be broken by the leads from the main antenna downlead cable.

The distribution antenna feeder network must be installed so as to reduce the overall inductance of the shields to a minimum for which the branch

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points of this network and the breaks in the shields must be joined by short jumpers. The feeder lead-ins must also be laid without breaking the cables.

The technical solution to the second problem is determined by the purpose, type and structural design of the antenna feeder.

The usual two-wire line used as the antenna feeder is a system of two parallel conductors rigidly connected to each other using insulators. It is characterized by small losses and comparatively high residual antenna effect. With an increase in frequency, the losses increase in them; therefore in the microwave band wave guides are used as the feeder.

When creating antenna feeders, the role of the shielding is highly significant, for the antenna is connected directly electrically either to quite powerful radiators or to the elements of the radio-electronic equipment most sensitive to the interference.

The experience in the construction of the stationary radio engineering objects, for example, indicates that the shielding of the feeders and the equipment transmitters will permit a decrease in the radiation field intensity in the range of 1 to 300 megahertz on the average by 25 to 40 decibels.

A significant decrease in the radiation intensity is also noted with improvement of the symmetry and matching of the feeder lines.

When shielding high-frequency feeder lines, simultaneously with achievement of the given effectiveness it is necessary to strive for the following:

The introduction of the shield should not increase the losses of oscillatory power passing through the feeder;

The established thermal conditions of the feeder, the shield and the elements of the radio-electronic equipment connected with them by the electrical circuits, through the devices and structural elements of the radio-electronic means should be maintained;

The introduction of the shield should not interfere with obtaining the required values of the traveling wave coefficient in the feeder or the asymmetric index;

The overall dimensions and weight of the shield were within the admissible limits, and its structural design withstood the limiting mechanical and climatic loads.

Shielded feeders of various types are produced [52]. The structural designs of the feeders in the rectangular and cylindrical shields are depicted in Figures 3.6 and 3.7.

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Any type of widely used feeder lines can be calculated. The overall dimensions of the rectangular shield of the two-wire line arranged symmetrically in it can be determined by using the graphs (Fig 3.8, a). The graphs [40] express the dependence of the wave impedance ρ_ϕ of the feeder on the ratio a/d for various D/d and b>a+3d for an air dielectric inside the shield. First, for the known ρ_ϕ, level of transmitted power (voltage or current) and the breakdown voltage of the dielectric, the diameter of the inside conductor d and spacing between the conductors a are selected or they are assumed given; then, by calculating a/d, D/d is found for the given ρ_ϕ. In accordance with the indicated inequality with respect to the values of a and d found, the minimum dimension $b_{min}=a+3d$ is determined. For a real shield we must have $b>b_{min}$. The stronger this inequality, the lower the losses in the shield. For example, for $\rho_\phi=300$ ohms and a power of 50 kilowatts it is possible to set d=10 mm, a/d=7. Then D/d=20, a=70 mm, D=200 mm, $b_{min}=100$ mm. In order to decrease the losses it is expedient to take $b=2.5b_{min}=250$ mm.

The corresponding graphs for the cylindrical shield are presented in Fig 3.8, b. For the above-investigated example when using a cylindrical shield we have d=10 mm, d/a=0.13; consequently, a=d/0.13=80, D/d=18, D=180.

In the required cases, the inside volume of the shield is filled with dielectric, which permits the decrease in the wire diameter, the distance between the wires and the dimensions of the shield.

In the presence of the corresponding data, the calculations of the single-wire feeder lines, shields with oval cross section, and so on can be presented.

The calculation of the power losses per unit length (watts/meter) in the shield of the two-wire feeder with air dielectric is made by the formula [23]

$$P_n=I^2a^2/\pi r^2\sigma\delta. \qquad (3.12)$$

where I is the effective value of the current in the feeder; a -- is the spacing between the feeder wires; r is the radius of the shield; σ is the specific conductivity of the shield material; δ is the depth of penetration of the current into the shield metal.

The power of the losses in the steel shield is comparatively high. For example, in the feeder shield 10 meters long on a frequency f=25 megahertz for copper and aluminum it is 1 watt, and for steel it is 24 watts. Therefore in order to decrease the losses and save nonferrous metals, it is recommended that galvanized iron be used as the shield material. Usually copper and aluminum are used in the coaxial feeders.

In order to avoid a decrease in the efficiency of the feeder shielding as a result of worsening of the quality of its insulation it is necessary to do the following:

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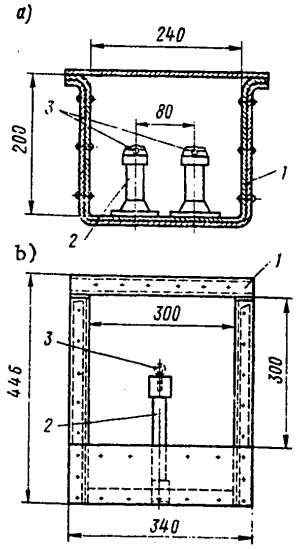

Figure 3.6. Structural design of the feeder line in a rectangular shield: a -- shielded symmetric feeder; b -- shielded asymmetric feeder (1 -- shield; 2 -- insulator; 3 -- wire)

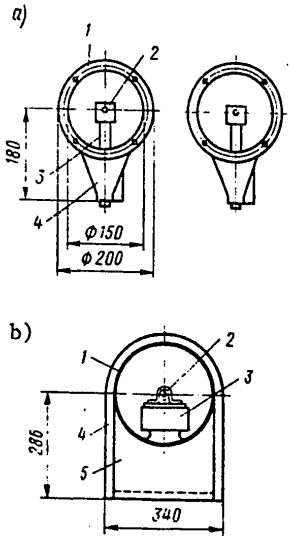

Figure 3.7. Structural design of the feeder line in a cylindrical shield: a -- shielded symmetric coaxial feeder; b -- shielded asymmetric coaxial feeder (1 -- tube; 2 -- rod; 3 -- insulator; 4 -- attachment of the insulator; 5 -- base)

Create a reliable electrical contact of the feeder shield with the basic shield of the radio-electronic equipment (at the point of exit of the feeder line from the bay) along the entire perimeter of the exit opening;

Analogously create a reliable electrical contact of the feeder shield to the antenna commutator shield;

Exit of the shielded feeders from the engineering building, the equipment room or cab of the mobile unit, retaining the electrical symmetry of the internal and external segments of the feeders and their shields and also matching the wave impedance of these segments;

In the case of radio means located on a mobile unit, the feeder shield must be grounded at the point of exit from the equipment room or joined to a common conductor ("mass" of the cab).

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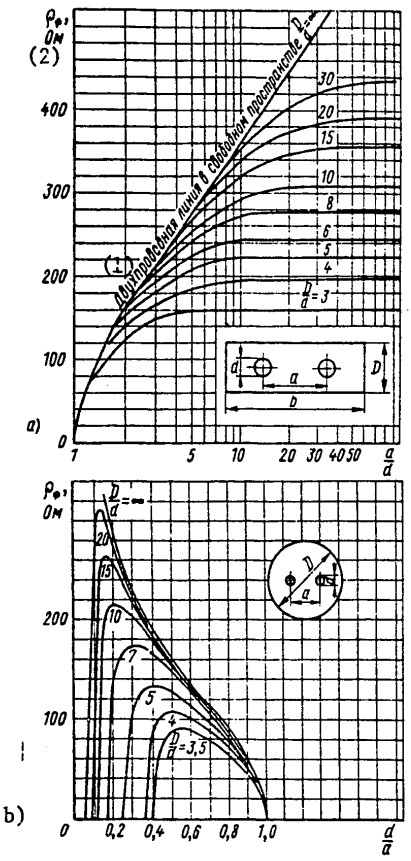

Figure 3.8. Graphs for determining the dimensions of the feeder shields

Key:
1. Two-wire line in free space
2. ohms

3.4. Radio Receivers

The capacity of the receiver to counteract the harmful influence of interference is characterized by the internal and external noiseproofness [52]. The internal noiseproofness is determined by the operating quality of the radio receiving equipment itself in the absence of noise, the sources of which are located outside the receiver, that is, the degree of correspondence of the levels of internal noise, amplitude, frequency and phase characteristics of the receiving channel to the type of received radio signal, its energy (amplitude), frequency and phase (time) parameters. The

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external noiseproofness or noise protection is the capacity of the radio-electronic equipment to perform its functions with required quality under the conditions of interference from sources outside the equipment.

The external interference penetrates into the receiving channel through its input units (the antenna feeders), through the interference-carrying networks formed by the electric power supply networks, the control and signal networks, and as a result of electromagnetic induction at the nodes, in the modules, the structural elements and the internal mounting of the equipment. Therefore the electromagnetic shielding and filtration of the interference-carrying networks are the most important measures for achieving the required noiseproofness of the radio receiver.

The effectiveness of the measures is estimated quantitatively by an equivalent level of external interference in the antenna at the input of the receiver or any intermediate part of the receiving channel preceding the final unit. In the presence of such estimates and known parameters of the radio channel, the determination and normalization of the corresponding signal-interference ratios in the given frequency bands are possible.

It is recommended that the overall interference protection of the radio receiver be estimated by the value [53]

$$I_{\text{(1) общ}}=h_{\text{(2) пд}}K_{\text{(3) п общ}}, \qquad (3.13)$$

Key: 1. general; 2. actual effective; 3. general interference transfer

where $h_{\text{actual effective}}$ is the actual effective height of the receiving antenna; $K_{\text{general interference transfer}}$ is the general interference transfer coefficient.

In addition, in order to estimate the quality of the receiver elements and the influence of various types of interference classified by the causes of their penetration into the receiving channel, it is proposed that the following partial characteristics be used:

1. The coefficient of noiseproofness of the receiving antenna feeder with respect to the interference propagated through the network;

$$I_{\text{a}}=h_{\text{пд}}K_{\text{a}}, \qquad (3.14)$$

where $K_a=U_{ist}/U_{pa}$ -- is the interference transfer coefficient from the interference-carrying network to the antenna (U_{ist} is the effective value of the interference voltage on the outside terminals of the receiver connected to the interference-carrying network; U_{pa} is the interference voltage at the output of the antenna feeder (at the input of the receiver)).

The effective height h_{rd} characterizes the capacity of the antenna feeder to trap the useful signal and transmit it to the receiver input:

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$$h_{\underset{(1)}{\text{рд}}}=\frac{E_a}{E_0},$$

Key: 1. actual effective

where E_0 is the signal field intensity; E_a is the emf developed at the input of the receiver by the signal with intensity E_0.

2. The coefficient of the network interference equal to the ratio of the interference voltage $U_п$ connected with the interference-carrying network which acts on the receiver to the voltage U_{pa} of the network interference at its input:

$$K_m=\frac{U_п(1)}{U_{па}.(2)} \qquad (3.15)$$

Key: 1. U_p; 2. U_{pa}

3. The coefficient of electromagnetic induction characterizing the susceptibility of the internal elements of the receiver to the electromagnetic induction fields:

$$\underset{(3)}{K_э}=\frac{E_{пэ}(1)}{U_{паэ}(2)} \qquad (3.16)$$

Key: 1. E_{pe}; 2. U_{pae}; 3. K_e

where E_{pe} is the intensity of the interference field acting on the receiver; U_{pae} is the emf induced in the receiver networks by this field.

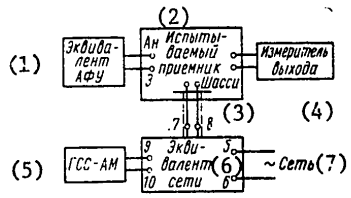

Figure 3.9. Schematic of the connection of the instruments when measuring the interference coefficient from the electric power supply network

Key:
1. Equivalent antenna feeder (AFU)
2. Tested receiver (AN)
3. Chassis
4. Output meter
5. Standard signal generator-AM (GSS-AM)
6. Equivalent network
7. ~ Network

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The coefficients can be calculated or determined by comparatively simple measurements on the operating radio-electronic equipment (Fig 3.9).

The tested receiver is installed on the insulated backing 80 cm high above a metal shield, the dimensions of which are no less than 1x2 m^2. The power cord of the receiver is shielded by a metal tube approximately 8 cm in diameter. The tube must have a reliable electrical contact on one side with the shield of the equivalent network (Fig 3.10), and on the other side, with the receiver chassis in direct proximity to its input. The modulated signal from the standard signal generator is fed through the network equivalent to the power supply circuit of the receiver, and it is taken as the interference voltage $U_п$. Then, for simulation of the voltage U_{pa} the signal of the same generator is fed to the input circuits of the receiver through the equivalent antenna. The voltages U_p and U_{pa} must be such that each of them will create the same level of modulating signal at the output of the receiver for identical amplification and under other equal conditions.

Usually the value of the coefficient K_m is for the radio broadcast receivers 50 to 60 decibels, for the television receivers 45 to 55 decibels, professional 60-80 decibels, and more.

The coefficient electromagnetic induction K_e is measured by the diagram analogous to the one depicted in Fig 3.9, but the power supply cord is not shielded, and the filter limiting the penetration of the interference from the power supply network is introduced into the feed circuit. When measuring this coefficient, considering the comparative complexity of the creation of a uniform interference field, it is replaced by the voltage U_{pe}, which is fed from the generator to the chassis and the "ground" channel of the receiver.

The coefficient K_e for radio broadcast AM receivers (range 0.15 to 30 megahertz) is within the limits of 40 to 55 decibels; for the receivers of FM signals and television signals operating on the frequency band above 30 megahertz, the coefficient K_e is controlled simultaneously with estimation of the effect of the interference of the power supply network.

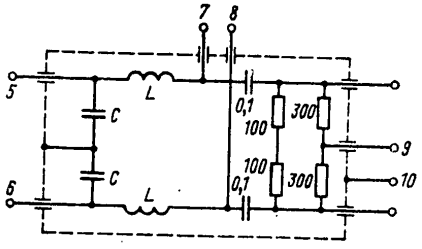

Figure 3.10. Schematic circuit diagram of the network equivalent

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In order to determine the interference protection of the antenna feeder it is necessary to measure the actual effective height of the antenna and the interference transfer coefficient. The actual effective height is determined by measuring the field intensity of the signal using an interference meter. Here the equivalent emf developed by the signal with a field intensity E_0 can also be determined using the interference meter.

The interference transfer coefficient from the network to the antenna is measured by including a generator in the electric power network for measurement of the transfer coefficient (GIPK). The voltage U_{ist} from the generator is measured at the points of connection of this generator (interference source) to the electric power network. The voltage at the input of the receiver occurring under the effect of the included generator is determined by the interference meter.

The noiseproofness of the antenna feeder is the potential noiseproofness of the entire radio receiver, and it serves as the base for establishing the norms for all of the partial noiseproofness characteristics. For example, the noiseproofness of the collective-use antennas (h_{rd}=0.5 meters) in the long wave and medium wave bands must be no less than 60 decibels; in the ultrashort wave band for FM radio broadcasting, no less than 65 decibels, and for the television receivers, 65 to 70 decibels.

The satisfaction of the indicated noiseproofness requirements and also the more rigid requirements for professional and specialized radio receiving equipment is insured by the technical solutions with respect to its structural design and, in particular, the measures with respect to filtration, general and element by element shielding.

The realization of recent norms with respect to shielding the receiving equipment, as a rule, gives rise to worsening of the overall dimensional characteristics, and it leads to a reduction in the technological nature and an increase in cost. When designing the receiver it is possible to provide for measures that insure high noiseproofness without significant reduction of the indicated characteristics. Thus, in the wave range of 0.1 to 100 meters the input circuit is connected to the antenna through the autotransformer and the matched feeder, in particular, through the coaxial cable protected from the external fields of the grounded external sheathing. During communications a matching transformer is connected to the antenna by unshielded symmetric feeder at the receiver input. As a rule, a lattice type electrostatic shield is installed between the coil of the oscillatory circuit of the input circuit and the coupling coil, eliminating the capacitive coupling between them.

The shielding effectiveness is the basic factor determining the noiseproofness of the receiver with respect to electromagnetic induction. When selecting the minimum required shielding effectiveness $E_{0\ min}$ of the receiver, the following parameters are taken into account: the signal-interference ratio $K_{c\pi}$; the general voltage amplification coefficient

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$K_{general}$; the partial voltage amplification coefficient from the given intermediate to the output stage $K_{partial}$; the maximum intensity $E_{п\ max}$ of the interference field at the reception point; the guaranteed field intensity of the signal $E_{c\ min}$; the actual effective height h_{rd} of the antenna.

The minimum required shielding effectiveness is

$$\underset{(1)}{\Theta_{0min}} = \underset{(2)}{\alpha K_э} = 0{,}3 \underset{(3)}{K_{сп}} \frac{\underset{(4)}{K_ч^{(3)}}}{\underset{(4)}{K_{общ}}} \frac{\underset{(6)}{E_{п\ max}}}{\underset{(5)}{h_{рд}} \underset{(7)}{E_{с\ min}}} \qquad (3.17)$$

Key: 1. K_e; 2. signal-interference; 3. partial; 4. general; 5. rd; 6. interference max; 7. signal min

and the maximum for $K_{partial}/K_{general}=1$, that is, in the case where it is considered with respect to the input stage. Here α is the proportionality coefficient, the magnitude of which is 0.25 to 0.35 by the measurement results in the frequency band to 300 megahertz. The coefficient of electromagnetic induction is

$$\underset{(1)}{K_э} = \underset{(2)}{K_{сп}} \frac{\underset{(4)}{K_ч^{(3)}}}{\underset{(4)}{K_{общ}}} \frac{\underset{(6)}{E_{п\ max}}}{\underset{(5)}{h_{рд}} \underset{(7)}{E_{с\ min}}}.$$

Key: 1. shield; 2. signal-interference; 3. partial; 4. general; 5. interference max; 6. rd; 7. signal min

In the simplest example for $K_{signal-interference}=30$, $h_{rd}=0.5$ meters and a ratio of the interference field intensity to the guaranteed emf of the signal $E_{interference\ max}/E_{signal\ min}=10$ the total required minimum shielding effectiveness with respect to the input turns out to be 45 decibels.

On the average the minimum necessary effectiveness of the shielding of the modern radio broadcast receivers will be 45 to 55 decibels; for the television receivers it reaches 65 decibels, and for the professional general-application radio receivers, usually it is no worse than 75 decibels.

In order to reach a receiver shielding effectivenss at the 50 decibel level, it is necessary to realize modular shielding of the assemblies most subject to the effects of interference such as the input devices, the first amplification stages, frequency converter, the intermediate frequency amplifiers and heterodynes. In addition, the heterodyne shielding must provide the required attenuation of the leakage of the voltages of their signals and harmonics to the receiver input, beyond the limits of the receiving channel and to other elements not functionally connected with these generators.

In television receivers, it is necessary to shield all types of generators, the high-voltage rectifier, the amplitude selector stages, the frame and line scanning circuits. In order to maintain continuity of the shielding, the connection of the indicated assemblies must be realized by shielded wire.

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Of course, all of these measures are performed with the corresponding filtration of the circuits, decoupling, blocking, carefully executed grounding, composition and installation of the elements.

In the professional receivers, as a rule, a general shield is used with maintenance of high electrical seal at the points of emergence of the control handles, the connection of auxiliary units, the location of the ventilation openings, and so on.

3.5. Electronic Amplifiers

The shielding and filtering of the amplifier networks are used to exclude the effect of external electromagnetic fields on the operation of the amplifier and also to eliminate the spurious couplings occurring as a result of insufficient effectiveness of the shielding of the stages. Therefore the noiseproofness of the amplifier is characterized by the coefficients of network interference K_m and electromagnetic induction K_e, each of which is a unique function of the suppression of the interference in the spurious processes in the amplifier which are provided by the structural design of the shield.

The total minimum necessary effectiveness of the shielding of the amplifier under the condition that $h_{rd}E_{signal\ min}=U_{input}$, considering (3.17) is

$$\mathcal{Э}_{0\,min}=0{,}3K_{сп}\frac{K_{ч}^{(2)}E_{n\,max}^{(4)}}{K_{общ}^{(3)}U_{вх}^{(5)}} \qquad (3.17')$$

(1) (2) (3) (4) (5)

Key: 1. signal-interference; 2. partial; 3. general; 4. interference max 5. input

In order to determine the maximum value of the required shielding effectiveness there is no necessity to know the general amplification coefficient $K_{general}$ of the channel, for on the input side the ratio $K_{partial}/K_{general}=1$. The effectiveness of the shielding of the subsequent stages is calculated by the same formula, but with substitution of the value of $K_{partial}$ equal to the amplification coefficient with respect to voltage in the section of the amplifying channel with respect to which the required effectiveness is determined. It is easy to see that if we are talking about the determination of the effectiveness of the shielding of the N-th stage, the expression (3.17') can be represented in the form

$$\mathcal{Э}_{0\,min}=0{,}3K_{сп}\frac{E_{n\,max}^{(2)}}{U_{вх\,N}^{(3)}}, \qquad (3.17'')$$

(1)

Key: 1. signal-interference; 2. interference max; 3. input N

where $U_{input\ N}$ is the input voltage of the N-th stage. Inasmuch as this voltage is greater than the input voltage of the first stage by an amount equal to the amplification coefficient of N-1 stages, the required shielding

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effectiveness can be reduced by as many times. Consequently, the normal operation of the amplifier can be insured with a decrease in shielding effectiveness from stage to stage, beginning with the second (from the input).

For example, let it be necessary to determine the effectiveness of the shielding of each stage of a three-stage amplifier for $K_{\text{signal-interference}}=40$, $E_{\text{interference max}}=0.5$ volts/meter, $U_{\text{inp}}=1$ millivolt, $K_{\text{gen}}=5\text{x}15\text{x}13$. The minimum required effectiveness of the shielding of the first stage must be as follows:

$$\mathcal{Э}_{0\,\min}=0{,}3K_{\text{сп}}\frac{K_{\text{ч}}^{(2)}}{K_{\text{общ}}}\frac{E_{\text{п max}}^{(4)}}{U_{\text{вх}}}=0{,}3\cdot 40\cdot 0{,}5\cdot 10^{3}=6\cdot 10^{3}.$$
(1) (2) (3) (4) (5)

Key: 1. signal-interference; 2. partial; 3. general; 4. interference max; 5. input

The required effectiveness of shielding the second stage under the condition that a signal with a voltage of 5 millivolts is fed to its input is 5 times less, that is, $E_{0\ \min\ 2}=1.2\cdot 10^{3}$, and for the output stage the effectiveness can be decreased by 75 times and it will be $E_{0\ \min\ 3}=80$.

For standardization of the structural design and in order to simplify the assembly process, the shields of the stages are made identical with respect to the input type. This provides the necessary margin with respect to effectiveness of the shielding of the entire amplifier. The specific amplifier stages usually are arranged in a line for the best decoupling from the currents in the chassis in the shielding cells. In tube amplifiers the tubes are installed outside the cells, and they are covered by separate electrostatic shields which, in addition to the basic value insure the necessary thermal operating conditions in the instrument.

It is expedient to execute the structural elements of the electron tube shields also by the principle of limiting wave guides. If it is necessary to limit the shield height, its upper part is covered with a filter of the "honeycomb" type (Fig 3.11, a); holes are made in the bottom. If the height of the shield is not limited, its upper part is left open (Fig 3.11, b). The closed shield must have ribs for better heat removal, for example, using the spring rings coupled to the bulb of a tube in its most heated section.

The position of the shield is fixed using a threaded ring and contact ring.

The housing shield of the amplifier is a longitudinal box of rectangular cross sections separated by partitions, the number of which is one less than the number of stages. The elements of each stage are mounted on the inside of the upper common removable plates so that no slits or openings are left.

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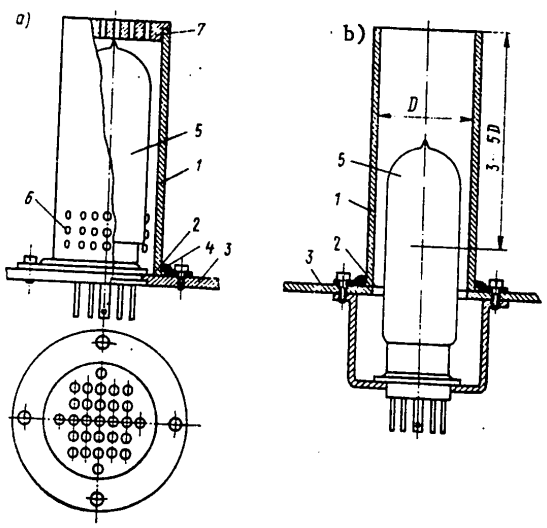

Figure 3.11. Shields for electron tubes:
1 -- tube shield; 2 -- contact spring; 3 -- chassis; 4 -- preset ring; 5 -- tube; 6 -- perforated part of the screen;
7 -- filter of the "network lattice" type

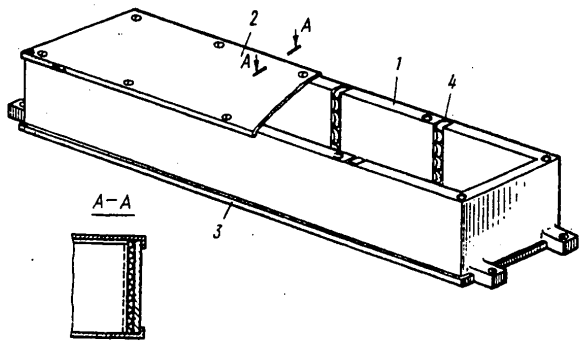

Figure 3.12. General view of the electronic amplifier in the longitudinal shield of rectangular cross section:
1 -- box; 2 -- upper plate; 3 -- lower plate; 4 -- guides for installing partitions

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In order to install the partitions, guides are used (see Fig 3.12). The slits at the points of connecting the shield and the partitions can be eliminated, rubbing these points with electrically conducting glue. The upper plate of the sides is attached by bolts, and in order to insure sufficient electrical seal, a rubber rope is laid along the sides and the partitions, above which the shielding braiding is stretched. Electron tubes and transistors with their shields, plugs, tuning elements and other assemblies to which access is needed, are installed on the outside of the upper plate.

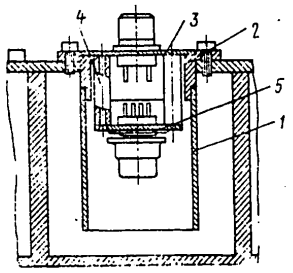

Figure 3.13. Amplifier stage in a tubular chassis

If the structural design of the amplifier stage or group of stages must be a separate module, the so-called tubular chassis is needed (see Fig 3.13). The chassis is made up of the connecting tube 1 of the required diameter with a flange 2 welded to it. If the structural design permits the use of a connecting tube of sufficient length, the side of it remains open like a wave guide filter. If the overall dimensions are limited, the connecting tube is closed with a filter of the honeycomb network type. On the opposite side the tubular chassis closed by a blind flange 3, to which the uprights 4 are fastened by screws. In turn, a circular plate 5 with a panel is screwed to the uprights by bolts. The parts and the stage installation are placed on the plate 5 and the uprights. The blind flange 3 is fastened to the flange of the tubular chassis by screws. In the flange there are openings for attaching the stage to the general chassis of the device. The inter-stage connections are made using shielded plugs. The structural design can be simplified if the connecting line is screwed to the flange 2; it is convenient for operation, and permits rapid replacement of the failed stage and it does not require a special shield for the electron tube.

3.6. Multichannel Long Distance Communications Equipment

In the long distance communications multiplexing equipment, the external electromagnetic fields can have an interfering effect on the main cables and the communication lines, the signal processing channels where the interference penetrates through the openings of the module jacket; the

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interference caused by the external fields is propagated also through the other networks, including the feed networks.

This takes place in the case where the interference frequency does not coincide with the channel pass band. As a result of the conversion of the interference frequency and its effect on the modulators and demodulators and also the interaction with the harmonics of the carrier frequencies it can turn out to be in the pass bands of the system.

To a high degree the effect of the external field depends on at what frequency in the sound channel they will be manifested, for the low-frequency spectrum has great nonuniformity and the oscillations in the various frequency bands of it are received differently. Finally, disturbances can occur in the operation of the long distance communications system during overloading of the amplifier or frequency converter. In this case, failure of the channels located both in the interference spectrum and outside it is possible.

The experience in operating and maintaining the long distance communications systems indicates that the majority of these systems are subject to the effect of various types of interference from the radio-electronic means and industrial installations, and so on. The control of this interference by increasing the signal level at the equipment input, improving the quality of the communications line or inclusion of the auxiliary amplifying-receiving devices alone frequently turns out to be ineffective. Therefore it is expedient to give some attention to increasing the shielding effectiveness of the long distance communications equipment and improvement of the filtration of its circuits.

In order to determine the shielding effectiveness of the DS equipment, as is obvious from (3.17), it is necessary to note the following:

1) Admissible signal-interference ratio $K_{\text{signal-interference}}$,

2) The magnitude of the expected maximum interference field $E_{\text{interference max}}$,

3) The coefficients of electromagnetic induction and network interference K_e and K_m. It has been established that in the frequency range of 10 kilohertz to 10 megahertz on the average it is possible to consider: $K_{\text{signal-interference}}=49$ decibels; $E_{\text{interference max}}=0.5$ volts/meter; $K_e>70$ decibels; $K_m\geq 75$ decibels; effective signal voltage at the input $U_{inp}\geq 0.1$ volt.

Then the minimum required shielding effectiveness of the equipment must be approximately 55 to 60 decibels, and the effectiveness of filtration of the electric power supply networks is no less than 60 decibels. The expediency of these requirements is confirmed by the experimental data.

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The insurance of such rigid requirements is possible only on the application of general and block screening of the equipment, careful filtration and decoupling of the circuits.

Experience shows that in the presence on the object of a general rectifying substation, in accordance with the rated currents and voltages the feed circuit must be connected to the distributing panel through interference-suppressing filters under the condition that the rectifier and panel are shielded. The power is supplied to the equipment in steel tubes which are welded around the entire perimeter on one side to the shield of the distributing panel and on the other, to the common shield of the instrument. With a small number of samples or types of equipment, the general cable layout of the feed network can be installed without a distributing panel and common filter. Every user must have its own filter installed inside the common shield or outside it. The leads from the rectifier to the filter must be laid in tubes.

The general and modular shielding of the equipment can be accomplished by using the pedestal of the common shield with the construction of individual shielded compartments and with auxiliary shields for each module. The mounting cable is laid in a special channel which itself performs a highly effective shield. The use of a bay type structure for the common shield in which the shielded modules are installed is expedient. In this case, it appears possible to make the common shield more effective. In the upper part of the bay it is expedient to use the honeycomb type filter to provide for natural cooling. The wave guide filter is installed at the top, and it is covered to protect it from outside effects. With this design it is comparatively simple to insure reliable contact between the modules and the common shield, between the rear wall and the bay.

Considering that a large number of control panels, measuring instruments, monitoring jacks are installed on the front panels of the modules, it is necessary to mount them so that the electric seal of the shield is not disturbed. The measuring instruments must be installed considering the recommendations presented in §3.2, and the leads from the axes of the tuning and adjustment elements and installation of the monitoring jacks must be in accordance with the standard structural designs of Table 2.3. The design using limiting wave guides is preferable for the monitoring jacks.

Around the contact perimeter of each module with the common shield, it must have a tinned rim to which the contact lay is attached. The modules are fastened to the common shield by bolts.

The module is joined to the inside installation by ordinary knife contacts or using the corresponding plugs.

3.7. Radio Transmitters

The radio transmitters and electromagnetic oscillators are used in many fields of engineering, in industry, medicine and scientific research.

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Depending on the purpose, the nature of the generated signals and the structural design of the oscillator, special requirements are imposed on the shielding and filtration system of the source of electromagnetic oscillations. There is an especially sharp delineation between the oscillators designed for information transmission and the oscillators used to support technological processes and in medical equipment. In the first case all of the energy generated by the oscillator must be emitted into space by antennas, and in the second case, used in the process (working) element.

The fact that in both cases the shielding and the filtration must exclude propagation of electromagnetic energy in directions not provided for by the operating principles of the device, outside the channels of its movement from the supply to the user, is a common factor. The methods of using the electromagnetic energy and distribution in time, in space and with respect to spectrum, the structure of the final user (receiver) of the electromagnetic oscillations, the danger of access to the working elements, the methods and algorithms for quality control of the functioning of the basic equipment and also other factors determining the structural design of the equipment and the shields are specific.

The modern mobile or stationary radio transmitter is a complicated set of equipment which includes the radio transmitter itself, the antenna feeder, the power plant, the elements of the control system, the system for monitoring the state of repair and electrical safety.

The estimation of the effectiveness of the shielding of such a complex radio engineering installation as the modern radio transmitter is a goal, the operative engineering solution of which is possible only on introduction of defined restrictions. It is obvious that the quantity and level of these restrictions will determine the accuracy of the solution.

Although in planning and design practice, depending on the proposed construction, a definite prediction of the effectiveness of the transmitter shielding is possible, the results of model testing are still decisive.

A differential estimate presupposes an experimental analysis of the effectiveness of the shielding of each element of the radio transmitter. This analysis is made using the measuring receivers, measuring generators or oscillators which form part of the net transmitter. The latter are used for testing under operating conditions.

The distributions of the regions of leakage of electromagnetic energy on the outside surface of the equipment with different values of the shielding effectiveness are determined by comparing the field structures inside and outside the shield. For this purpose, spectral characteristics of the power supply mission inside the equipment must be obtained, and the measuring receiver for analyzing the external field must have an antenna which is calibrated in the given frequency range with respect to the

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effective altitude, with known radiation pattern. The field inside the shield is measured, as a rule, near its inside surface. If the distance from the emitting element to the shield does not exceed the emission wave length, it is possible to consider the field at such small distances from the emitter to be quasistatic and to measure or calculate it by methods corresponding to the static electric and magnetic fields. Here the necessity can be dropped for using the measuring receiver, the readings of which can be predicted by comparatively simple calculations. For example, when locating the coil of the output circuit of a powerful stage or the high-frequency mounting conductor joining the circuit to the tube or transistor, at about 2 meters above the earth and with a wire diameter of about 1 cm, the effective intensity of the electric component of the field at a distance of 1 meter in the frequency range to 30 megahertz will be $E \approx 0.3U_k$ [volts/m], where U_k is the effective voltage in the circuit (the conductor).

It is possible to proceed analogously if the field also on the outside of the shield is monitored at small (also less than the wave length) distances from it and the emitter. However, here the calculation difficulties increase, especially with complex configuration of the shielding surface. The introduction of the additional restrictions will sharply increase the calculation error, and therefore when determining the external fields it is almost always necessary to use measuring receivers.

The frequency range in which the measurements are taken for all forms of estimation or determination of the shielding effectiveness must encompass the section where the basic, extraband and side oscillations of the transmitters are distributed. In addition, the shielding effectiveness must be checked out in the frequency bands where the effect of the side emitters and the occurrence of the combination oscillations propagated into the surrounding space both through the antenna feeder and bypassing it is possible.

After multiple measurements the materials obtained in this way are processed statistically. The final result usually is considered to be the minimum mean or minimum most probable value of the shielding effectiveness as a function of frequency represented graphically, analytically or by tables. These data provide grounds for determining the requirements with respect to the effectiveness of the shield and making the corresponding decisions in the design process with respect to each of the investigated regions of the shield surface.

A differential analysis of the filtration effectiveness of the interference-carrying networks is made analogously. The difference is that for this estimate instead of measuring the fields, the voltages in the different circuits are determined for the given electric length of the line from the interference source to the cross section of it beyond which their effect can be neglected. Selective voltmeters are used to measure the interference voltage.

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The minimum mean or minimum most probable value characteristic of one or several elements of it is considered to be the common (resultant) effectiveness of the shielding and filtration of the transmitter or another device as a whole.

The differential experimental estimate of the shielding effectiveness in many cases turns out to be complicated and is used only for the most responsible elements of the equipment. Usually the powerful stages of the transmitter, the channels of the large number of nonlinear signal converters, the devices for formation of the range and the working frequency grid, the amplification and modulation units and channels determining the emission characteristics of the transmitter are of this type. The selection of the most responsible moments depends on the experience in designing and operating the radio-electronic equipment, the requirements on it and the requirements with respect to the emf of the radio-electronic means joined into a concentrated group. This experience provides the basis for using a significantly more operative experimental estimate of the shielding effectiveness which can be provisionally called integral. The essence of this system consists in the fact that after determining the weakest element of the radio-electronic equipment with respect to shielding, the designer assumes its properties to be characteristic of all the equipment. As a result of the integral estimate the measures with respect to interference suppression are taken for all of the equipment, but considering the specific nature of the structure and design of each element. The effectiveness and correction of the measures are checked analogously. During the course of their execution, the radio-electronic equipment elements which are monitored and found to be weak with respect to shielding characteristics can be altered.

The procedure where one of the following elements is selected as the monitored element, depending on the specific nature of the construction of the transmitter can be used as an example of the operative experimental estimation of the shielding effectiveness as applied to the radio transmitter: the output module of a powerful channel, the output circuit of a powerful stage, the output circuit of the most powerful electronic device in the radio channel of the transmitter, the harmonic filter, the device for matching the powerful channel to an antenna feeder system, and so on.

It has special significance to estimate the required shielding effectiveness for which it is necessary to know the field near the inside surface of the shield (or source of interference) and the admissible residual field intensity at a given distance r from the outside surface of the transmitter shield (or the investigated element of it -- the interference source).

In the above-presented example, the required relative shielding effectiveness is

$$\Theta_0 \geqslant 0{,}3U_{\text{к}}/E_N r^2, \qquad (3.18)$$

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where E_N is the standardized admissible effective value of the residual intensity of the electric component of the field at a distance r from the transmitter.

For r=1 m, in the dividers the same effectiveness will be

$$\vartheta = 20 \lg U_R - 20 \lg E_N - 10. \qquad (3.19)$$

It is more complicated to estimate the effectiveness of the shielding of several radio transmitters placed in the common shielded equipment room. Usually this operation is broken down into two steps. First the shielding effectiveness of each transmitter is determined. Here the effect of emitters not belonging to it must be excluded. Therefore the shielding of one transmitter under operating conditions is checked with the others switched off. In the second step an estimate is made of the shielding effectiveness of the entire group by a common shield in the frequency band where the basic side and extraband emissions of the individual transmitters are located and also the combination side and extraband emissions occurring as a result of their mutual effect. The field inside and outside the common shield is characterized by the effective value of the intensity in the frequency band $f \pm \Delta f$ as a function of the frequency f and the distance r to the emitter or the shield:

$$E = \sqrt{\sum_{i=1}^{n} E_i^2(r, f)}. \qquad (3.20)$$

In expression (3.20) $E_i(r,f)$ is the spectral component of the radiation in the given frequency band; n is the total number of emitters in the same band.

The required values of the shielding effectiveness of the radio transmitters in the equipment rooms usually are determined by the special technical requirements on them which are substantiated by the conditions of insuring electromagnetic compatibility of the radio-electronic means of specific grouping, possibilities and specific characteristics of the structure of the units and also the biological shielding standards [39, 54].

These standards are generalized by the so-called sanitation rules regulating the admissible residual electric field intensity, the effect of which is still harmless to the operator. Thus, for example, when using approximately 15 to 20 5-kilowatt transmitters and approximately 3-5 transmitters with a power of more than 5 kilowatts at a transmitting radio broadcast station, the shielding effectiveness of each transmitter must be such that the residual electric field at a distance of 0.5 meters from each bay with a terminal power amplifier does not exceed 5 volts/meter in the frequency range of 0.15 to 300 megahertz.

The satisfaction of the sanitary rules is checked by the electromagnetic field meters by the procedure discussed in [28]. The shielding of the equipment rooms of stationary installations where it is necessary to see that only the sanitary rules are satisfied usually is not provided inasmuch as the required norms can be met by shielding only the equipment itself.

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Prolonged studies of electromagnetic fields of transmitter emission in the equipment rooms of the transmitting radio broadcast stations have shown that the effect of the electrical components of these fields turns out to be predominant. In the vast majority of cases the power of the magnetic component of the field even in direct proximity to the generator $P_H < 0.25 \cdot 10^{-6} P_E$. Near the open oscillatory circuits with the powerful stages $P_H < 0.1 P_E$.

The measures to protect against the electromagnetic fields of radio transmitters include the following:

Modular and complete shielding of the generators, the elements for the formation of modulated radio signals and the exciter of the transmitter to prevent direct emission of the basic, side and extraband oscillations which, in particular, include the oscillations accompanying the formation of the basic signal, its harmonic components, the spurious self-excitation oscillations, and the noise;

The shielding of the channel elements of the power amplifier and the devices for matching it with the antenna feeders to prevent direct emission of the oscillations (and also for attenuation of the effect on this channel of the field of the nearby emitters leading to the occurrence of combination and intermodulation interference);

The shielding of the devices used for commutation of the high-frequency circuits of the radio and video channels, the commutation fields of the control panels, the intermediate monitoring, measuring and display circuits;

The shielding of the antenna feeders and commutators, the harmonic filters, the monitoring, measuring and display circuits of the powerful radio channel and other high-frequency cables.

Filtration of the networks, cables and leads from the power supply, the modulation and manipulation, control and signalling circuits.

The entire shielding system of the transmitter is thus made up of shielding individual elements, groups of elements and common shielding. If we begin with the fact that the initial effectiveness of the common shield is insignificant, then it is possible to obtain the required effectiveness in the final analysis by gradual improvement of the shielding of the individual assemblies.

The experimental studies of radio transmitters of various types in which the initial effectiveness of the common shield does not exceed 15 to 20 decibels have shown that the shielding effectiveness of any element determines the total effectiveness to a different degree. The shielding defects of the high-frequency cables and feeders have the greatest effect. The emission of open feeders, especially with a low traveling wave coefficient is predominant.

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The electric and magnetic seals are highly significantly influenced by the structural design of the tuning elements of a powerful channel and the devices for matching the power amplifier to the antenna feeder, the external housing or bay of the transmitter. These disturbances are equivalent to the occurrence of open emitters of electromagnetic oscillations of significant power correspondingly distributed on the surface of the equipment and having radiation patterns of random configuration. This effect can be attenuated not only by improving the structural design of the tuning elements and the shielding elements, but also reducing the number of smoothly or discontinuously tunable elements, by transition from manual control to semi-automatic or automatic control using devices hidden by the shield. Instead of continuous tuning it is expedient to use internal switching of the elements and stages by relays or hercons, electronic tuning devices with varicaps, coils with ferrites, reactive tubes, and so on. Under other equal conditions, identical shielding techniques and levels, the transmitters operating on fixed frequencies, narrow and wide-band transmitters with band channels and harmonic filters which are switchable by the control circuits have the best shielding effectiveness. In the untunable and modern wide-band transmitters, the problem of the disturbances of the shielding seal as a result of poor design of the tuning elements in practice is eliminated.

In the graphs in Fig 3.14 it is shown how the various improvements of transmitter design in the 1.0 to 300 megahertz range influence the shielding effectiveness.

Initially they had numerous openings for various purposes, and it was a shield, the average effectiveness of which did not exceed 20 decibels on a frequency of 1 megahertz (curve 1). With an increase in frequency, the shielding effectiveness from the bay decreases, and on a frequency of 300 megahertz its mean value decreases to 4-5 decibels.

When creating reliable electrical contact between the axes and the other parts of the mechanisms, the tuning elements and control elements of the powerful channel with the basic shield (bay) around the perimeters of the openings, the shielding effectiveness increased and was on the average 10 to 15 decibels (see curve 2).

The additional shielding of the measuring displays on the inside of the bay by metal hoods raised the mean effectiveness by 10 to 12 decibels more (see curve 3) by comparison with the preceding curves.

If in addition to these measurements the inspection holes are protected by a fine metal screen, on the average the effectiveness will be characterized by curve 4.

The remaining curves indicate how the effectiveness will increase if, in addition to the enumerated improvements, a tight contact around the entire perimeter of the opening doors (curve 5) is insured, the sheets of the skin are joined by a solid welded or soldered seam (curve 6), the openings

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for communication lines are shielded (curve 7) and the air cooling system is shielded (curve 8). The subsequent creation of shielded compartments inside the bay for elements of the oscillatory circuits is a gain in average effectiveness of approximately 20 to 25 decibels.

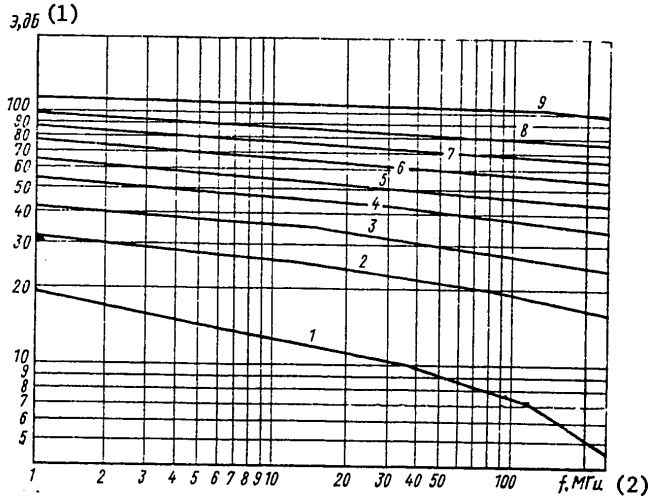

Figure 3.14. Effectiveness of shielding the radio transmitter for various methods of improving the electric seal of the shield

Key:
1. decibels
2. megahertz

As a result of performing these measures, on a frequency of 1 megahertz it is possible to achieve a shielding effectiveness to 100-120 decibels, decreasing with an increase in frequency in the entire investigated range by no more than 10 decibels.

Thus, it is possible to characterize the effectiveness of the measures with respect to shielding the antenna feeder system of a transmitter.

Curve 1 (Fig 3.15) characterizes the provisional mean effectiveness of the shielding of an open antenna feeder with a traveling wave coefficient of no less than 0.8. Even with this high degree of matching and perfect symmetry, it still has a perceptible antenna effect inasmuch as the provisional mean effectiveness of the shielding does not exceed 35 to 40 decibels here.

The shielding of the feeder diminishes the influence of the antenna effect (curve 2) sharply, and the effectiveness reaches 60 decibels.

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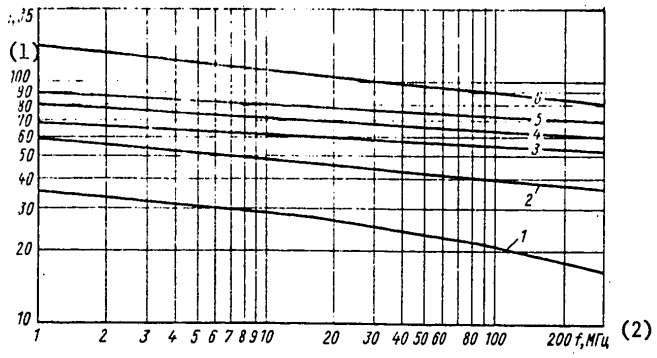

Figure 3.15. Effectiveness of shielding the antenna feeder of a transmitter with various methods of increasing the electric seal of the feeder shield

Key:
1. decibels
2. megahertz

Further improvement of the effectiveness of the shielding can be obtained, creating an electric contact between the feeder shield and the transmitter bay with respect to the entire perimeter of the opening for exit of the feeder from the shield of a powerful stage, the harmonic filter or the device for symmetrizing and matching the antenna (curve 3).

Curve 4 illustrates the effect of shielding the transmitted power displays, curve 5 illustrates the shielding of the antenna commutators and finally, curve 6, the result of tight coupling of the individual sections of the feeder shield by laying fine-mesh screen, measures to retain electric symmetry and match the sections of the shielded feeders and also ground the feeder shield.

It must be noted that in itself the given structural design of the shield part of a transmitter or feeder still does not determine the actual shielding effectiveness, but only determines its potential upper boundary.

Depending on the specific conditions and improvement of the structural design, the same assembly will give different effectiveness, so that the increase in the overall effectiveness introduced by this unit will also be different.

Therefore the presented curves characterizing the process of increasing the effectiveness of the shield must be considered as an illustration of the special examples which, however, are quite similar in practice. It is obvious that an increase in the shielding effectiveness with a gradual improvement in structural design of the shield depends on its initial state,

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size, nature and location of the radiation sources. In the decimeter and centimeter bands, oscillatory systems are used which are to a significant degree self-shielded. For example, in the oscillators operating on tubes having disc or cylindrical electrode leads, a wave band of 10 to 100 cm, usually closed dipoles are used which in practice do not require additional shielding. With expedient design of the dipole and the blocked elements the emission losses here are highly insignificant.

However, the presence of openings and slits in the dipole itself, if they are made with deviation from the requirements of shielding engineering, can lead to a significant increase in the emission levels and disturbance of the operation of the other devices.

When designing the transmitters of decimeter and centimeter waves, the attention of the designer must be concentrated primarily on selecting the designs of the high frequency contact systems, the oscillatory system of the output stage, the joining of the generator tube to the closed dipole, the tuning elements and blocking elements. These problems have been discussed in quite some detail in [55, 56].

Usually one or several metal bays in which the circuit elements are mounted constitute the basis for the design of the transmitter. The portable transmitters and low-power transmitters of mobile units are mounted in one or several metal modules, packings or containers. In the powerful long and medium wave transmitters frequently shielded compartments, bays or shielded facilities are used in which only the output circuits or other large oscillatory systems, harmonic filters and elements for matching with the antenna are placed. Inside the basic modules or the transmitter bay closed or open compartments are created for its basic functional elements which frequently are made in the form of individual instruments or technologically improved products. In each of the bays or basic modules one or several stages of a powerful channel, an exciter, the electric power supplies, and so on can be placed.

In order to localize the electromagnetic energy in defined volumes and protect against side emitters to insure conditions of external and internal electromagnetic compatibility of radio transmitters, each bay, basic module, or transmitter housing must be in the form of a shield or system of shields joined by a common structural design, layout of the cable connections and communications entries (exits) and a common ground. Therefore the structural design of the housing must be created giving equal consideration to the composition conditions of the elements, assemblies and modules determined by their functional relations, the peculiarities of the radio transmitter control system, the recommendations of engineering esthetics and psychology and also the possibilities of shielding the transmitter with given effectiveness.

Although independently of the method of placement of the equipment, the transmitter control is usually from a remote panel, the majority of the radio transmitter elements have their own mechanisms and control elements

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led directly to the corresponding panels. This fact and also the presence of a branched cable network, cooling system, communications input and output structures essentially complicates the structural design of the primary shield.

The composition of the transmitter or group of transmitter elements can be on a general frame in the form of a bay (Fig 3.16, a), a pedestal with plug-in modules (Fig 3.16, b), in a housing of the suitcase (Fig 3.16, d) or other type (Fig 3.16, c). In the latter case, each module has its own shield, and the module is secured in a receptacle set aside for it. The effectiveness of the shielding of each module is determined as a function of its sources of interference and devices sensitive to this interference. Frequently the modular shields are made standardized insuring the highest required effectiveness. The intermodular connections are made using a closed contact system or cylindrical plugs with mandatory observation of the rules for efficient layout of the installation lines for excluding the mutual effect of the modules not provided for by the schematic diagram.

When using a bay type or bay-container type pedestal, the bay-container is a common shield for all modules of which some can have auxiliary shields. The intermodular installation is made inside the bay with the appropriate conductor layout. In a powerful radio transmitter this type of composition is used more frequently as more universal, insuring compactness of the overall structural design, better operating and maintenance conditions, repairability and technological nature and also the possibility of using combined (general and modular) shielding with required effectiveness.

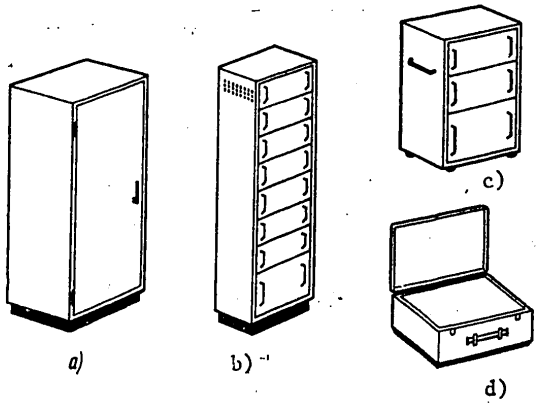

Figure 3.16. Structural designs of radio transmitters

The frames of the pedestals are made of steel angle irons of standard profile or sheet steel. The sheathing is fastened by spot welding,

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continuous welding or bolts. The spacing between the fastening (welding) spots can be determined by the formulas (2.6), (2.7).

When designing shielded housings for the modules of radio transmitters, it is necessary to adhere to the following recommendations:

The housing must insure localization of high-frequency energy in its volume or protection against external fields within the limits of the required effectiveness.

The choice of the material (metal) for the housing in practice is not determined by the electrical parameters of this material with the exception of the cases of intense reaction to the shielded elements when it is necessary to use nonferrous metals to obtain the minimum dimensions of the modules;

The thickness of the metal is determined by the conditions of the installation of the shield and its effectiveness and in practice it reaches 2 to 3 mm;

In order to insure electrical contact around the perimeter of the parts of the shield housing joined together, high finish of the contact surfaces (an additional tin coating is used on steel and copper shields), dressing of the welded frame and the sheathing sheets, tightening of the seams between the sheets and the frame by bolts with spacing corresponding to the minimum wave length of the radiation are required; the hole diameter under the screw must meet the tolerance standards for riveting;

It is necessary to insure electrical contact around the perimeters of all the opening parts (doors, telescopic modules, and so on) with the shield housing; the type of contact system (see Table 2.3) is selected according to the required effectiveness with respect to reliability, service life and other requirements;

All of the holes in the housing required for observation, cooling, ventilation, exit of the control element parts and the through passage of other communications and also holes in which the measuring instruments are installed must be formed so that the radiation intensity of the electromagnetic oscillations will be within the limits of the admissible values;

At the points of passage of the conducting circuits through the shield, they are filtered; through capacitors designed for the corresponding operating voltages can be used as the filters;

It is expedient to run the high-voltage leads into the shield through ceramic capacitors of the wall type;

The measuring and control circuits are shielded, the wire and cable network between the modules must not create inductions or spurious couplings;

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The seals used for water and foam protection must be combination and contain sealing strips of foam rubber, reinforced by metal (copper) braid;

If the shield is made of individual compartments which are insulated from each other, then in the presence of a common cover their seal can be made by using a rubber gasket with brass screen (see Table 2.3).

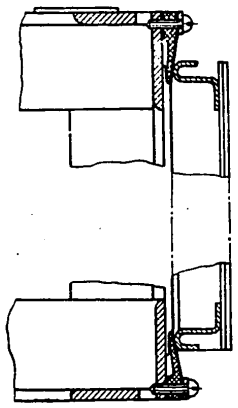

Figure 3.17. Structure of the Contact System for the Door Opening of a Transmitter Bay

The most responsible part of the common shield (bay) of the transmitter is the door, especially if it is made without its own frame. In addition to the contact systems presented in Table 2.3, in order to insure reliable contact around the perimeter of the door, a contact system shown in Fig 3.17 or the system with replacement of the contact plate by a contact spring is used (see Fig 3.18).

The inspection openings, the leads of the axes and parts of the control mechanisms, and the shielding of the openings are made in accordance with the data in Table 2.3.

The air cooling system is shielded using filters of the honeycomb or perforated insert type. When it is necessary to introduce water cooling pipes into the shield (the bottom of the transmitter bay), they must be laid through the connecting line welded to the housing of the corresponding length. It is expedient to use high-pressure rubber tubes or metal tubes welded to the entire perimeter of the cross section to the outside surface of the connecting line.

The structural design of the leads of the electric circuits of different purposes must provide for the maintenance of the total shielding effectiveness on the required level.

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The high-voltage, on DC wires and buses must be introduced into the bays of the powerful and pre-powerful stages through the high-voltage through capacitors. The low-voltage wires are recommended for introduction using the ShR type connectors, and the filtration of these wires is realized using the through capacitors of the KBP-F and KBPS type. The capacitors must be mounte directly at the lead-ins, providing for separation of the capacitor input from its output with respect to electromagnetic field using corresponding fastening.

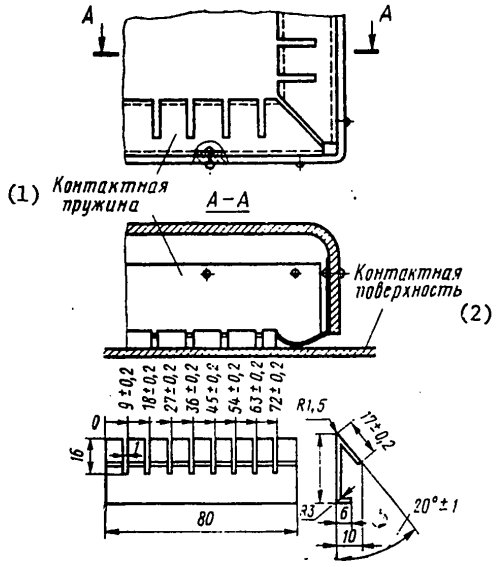

Figure 3.18. Fastening and structure of the contact spring

Key:
1. Contact spring
2. Contact surface

The leads of the high-frequency cables must be executed using the radio frequency connectors of the ShR type or others which maintain continuity in the shield in which each of the wires or group of wires is laid and maintain a seal of the connection between the wire shield and the transmitter shield.

In all cases where the transmitter is loaded on the symmetric feeder through the matching device or without it, and the higher harmonic filters installed on the transmitter output, it is necessary to separate the filter input from its output with respect to the electromagnetic field and simultaneously to eliminate the possibility of emission of the feeder in the

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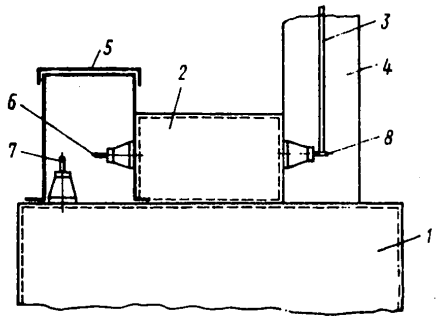

Figure 3.19. Sketch of the structural design of the shield for the harmonic filter:
1 -- powerful transmitter stage; 2 -- harmonic filters; 3 -- two-wire open feeder; 4 -- feeder shield; 5 -- shielding hood; 6 -- filter input; 7 -- transmitter output
8 -- filter output

section between the transmitter output and the filter input. For this purpose various shielding hoods with respect to structural design can be used which have electrical contact with the transmitter bays on which they are installed (Fig 3.19).

All of the recommendations with respect to fastening the sheathing of the contact systems are completely applicable also for the shielding hoods.

3.8. High-Frequency Industrial Generators

The high-frequency devices for industrial purposes are sources of industrial radio interference. Usually they are made up of three basic modules: the generator, rectifying and processing units themselves. Depending on the purpose of the installation, the process unit can be a furnace for melting metals, a capacitor for drying materials, a covered capacitor for heating the dielectrics, and so on.

The high-frequency oscillators are constructed for economy and simplicity of operation and maintenance in accordance with the simplest system made up of one or two stages. Frequently the functions of the autooscillator and the amplifier are combined in one stage, and the autooscillator itself is calculated for the entire necessary oscillatory power. The requirements of simplicity, economicalness and high efficiency of the unit lead to the fact that its oscillator and amplifiers operate under essentially non-linear conditions, and the application of effective filtration, feed voltage and frequency stabilization measures have been in practice excluded. As a result, the levels of side and extraband oscillations and also noise turn out to be significant.

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The presence of higher harmonic components of the operating frequency of very high order, spurious AM and FM oscillations leads to the fact that the output spectrum is grouped in the region of each of the harmonics with attenuation with respect to the first harmonic by a total of 20 to 30 decibels and the width of the effective band of the harmonic spectrum approximately proportion to its number.[1] The harmonic levels beginning with 3-5, decrease slowly so that the harmonics up to 30-40 have a perceptible influence on the standard radio receiver.

The distribution of the harmonic spectra with an increase in their order leads to the fact that the common side emission spectrum of the generator can be considered discrete only in the band to a harmonic of defined order. Actually, if the band of the basic radiation $f_0 \pm \Delta f$, the spectral band limits in the n-th harmonic region will be $n(f_0 \pm \Delta f)$. Then for some boundary value $n_{boundary}$, overlap of the spectra of the adjacent harmonics by the amount $\Delta F << \Delta f$ takes place, that is,

$$n_{гр}(f_0+\Delta f)-\Delta F=(n_{гр}+1)(f_0-\Delta f).$$

Hence $n_{boundary}=f_0/2\Delta f+\Delta F/2\Delta f-1/2$ or $n_{boundary}\approx[f_0/\Delta f]$, where the brackets indicate the integral part of the number.

Thus, the expansion of the harmonic spectrum by the law of arithmetic progression leads to the fact that in the $n_{boundary} f_0$ region and higher the output spectrum of the generator becomes continuous.

If special measures are not taken, up to 5-10% of the total oscillatory power of the industrial high-frequency devices can be concentrated in the spectra of the extraband, side oscillations and noise [23]. This does not prevent the use of the oscillators with respect to their purpose, but at high power (>100 kilowatts) it essentially increases the level of industrial radio interference. Since the industrial high-frequency devices operate in frequency bands within the range of 18 kilohertz to 22, 125 gigahertz [2], their interference can be distributed in practice with respect to all of the radio frequency band, causing additional loading of it. Usually the emitting (noise forming) elements of the high-frequency industrial devices are oscillatory circuits, electrodes, capacitors and coils of the technological unit, transmission lines, and so on. For low-effective protection and a generator power to 60 kilowatts the field intensity near the device can be more than 1000 volts/meter.

The basic measures to suppress interference from the industrial high-frequency generators can include the following:

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[1] The proportionality of the harmonic spectral width to its number with frequency modulation is easily proved, using the known Ye. I. Manayev formula.

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Regulation of the use of the generators with respect to power, operating frequencies, time and location;

Normalization of the noise levels, the extraband and side radiation and insurance of the satisfaction of these norms;

The application of frequency stabilization within the required limits, improvement of linearity and a decrease in the intensity of the conditions, filtration of high-frequency circuits and electromagnetic shielding.

Among these measures the electromagnetic shielding turns out to be the most effective, first because under the conditions of stationary units there are no rigid requirements with respect to dimensions and weight of the structural element, and secondly it permits concentration in the defined volume with the required attenuation of all of the high-frequency energy of the generator and, thirdly, the shielding permits a significant reduction in the radiation of both the imperfect generator and its technological unit. Here, just as before, by shielding we mean the set of measures encompassing the electromagnetic shielding of the generator itself and also filtration of the circuits which go beyond the limits of the shields.

The effectiveness of shielding the high-frequency devices for industrial purposes, just as many other types of radio-electronic equipment, must be selected from the conditions of satisfying the requirements of the sanitary rules for biological shielding and the norms for admissible radio interference levels.

Practice shows that when satisfying the sanitary rules in direct proximity to the generator, the norms for industrial radio interference are observed. However, in order to insure electromagnetic compatibility of the radio-electronic means in many cases the satisfaction of the sanitary rules turns out to be insufficient.

The value of the electric component of the intensity of an electromagnetic field from a source of radiation in the radio frequency range effective in the transition frequency band of a standard interference meter is as follows [23]

$$E\ [\text{В/м}] \approx 21\, h_a \sqrt{P_e}/r^2, \qquad (3.21)$$

where r is the distance from the source to the point at which the field intensity is determined, meters; h_a is the effective height of the meter antenna considering the height of its rise above the earth, meters, P_e is the equivalent power of the radiation source, watts.

In order to avoid prolonged measurements of the spectral characteristics of industrial radio interference and to obtain the unique estimate of the possibility of realizing the norms, independently of the emission frequency, we set h_a=2 meters, and P_e=0.001 P_g, where P_g is the total oscillatory

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power of the industrial generator. The same condition turned out to be valid in the majority of cases if at minimum distances the effectiveness of the shielding of the electrical component of the field with respect to the preliminary data is 50 to 60 decibels. In the absence of the shield $P_e=P_з$.

The sanitary norms for biological protection are formulated most frequently without indicating the distance r, for on going away from the emitter, the field decreases sharply. The satisfaction of the norms is checked in the areas of the facility where personnel can be located. At the work areas, the field intensity must be equal to no less than the maximum admissible value of E_N. At the same time, the more rigid norms with respect to the value E_N for the admissible level of radio interference determining the conditions of electromagnetic compatibility with the sensitive elements of the radio electronic means and domestic radio equipment always take into account the distance to the radiation source. Therefore the problem arises of the ratio of the required shielding effectiveness $Э_{0сп}$, defined by the sanitary rules and the effectiveness $Э_{0рп}$, caused by the norms for radio interference. It is obvious that for the same emission source the solution will be the most economical for which $Э_{0сп}/Э_{0рп}=1$. If we set $P_0=P_{эN}$, in (3.21) where $P_{эN}$ is the limiting emission power for which satisfaction of the norms on radio interference levels will still be insured,

$$\frac{Э_{0сп}}{Э_{0рп}}=\frac{E_{N\,рп}}{E_{N\,сп}}=\frac{2lh_a\sqrt{P_{эN}}}{E_{N\,сп}r^2}=1. \qquad (3.21')$$

Here $E_{Nрп}$ and $E_{Nсп}$ are the admissible field intensities with respect to the norms for radio interference and by the sanitary rules, respectively.

The condition (3.21') corresponds to a limiting distance at which the requirements both with respect to biological shielding and with respect to industrial interference are satisfied simultaneously:

$$r_{гр}=\sqrt{\frac{2lh_a}{E_{N\,сп}}\sqrt{P_{эN}}}=4{,}5\sqrt{\frac{lh_a}{E_{N\,сп}}\sqrt{P_{эN}}}. \qquad (3.22)$$

Key: 1. $r_{boundary}$

For $r<r_{boundary}$ the shielding insures protection against radiation, and for $r>r_{boundary}$ also the required noise suppression. If the radio-electronic means sensitive to interference are located closer than $r_{boundary}$ to the generator, the shielding effectiveness must be increased, but in this case it is necessary to satisfy the condition

$$P_э \leqslant P_{эN}=\frac{r^4}{(2lh_a)^2}E^2_{N\,сп}. \qquad (3.22')$$

The stronger the inequality (3.22'), the less it is necessary to increase the shielding effectiveness.

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Under the above-indicated restrictions h_a=1 meter), considering that in the 0.15 to 30 megahertz range, $E'_{N_{C\pi}}$=20 volts/meter, in the 30-300 megahertz band $E''_{N_{C\pi}}$=5 volts/meter, and in the band above 300 megahertz, the admissible power flux density $N_{N_{C\pi}}$=10 microwatts/cm^2=0.1 watts/m^2, which in the emission zone corresponds to $E'''_{N_{C\pi}}$≈6 volts/meter, we obtain

$$r'_{rp}=\sqrt[4]{P'_{3N}};$$
$$r''_{rp}=2\sqrt[4]{P''_{3N}}; \qquad (3.23)$$
$$r'''_{rp}\approx 2\sqrt[4]{P'''_{3N}}.$$

where P'_{3N}, P''_{3N}, P'''_{3N} are the limiting values of the emission power in the corresponding frequency band.

Usually the shielding effectiveness required to satisfy the sanitary rules is determined first, and then the possibility of satisfying the norms for industrial radio interference and the emf conditions. The estimation of the required shielding effectiveness by the magnetic component is not made if it is known by the nature and frequency range of the emitter that the energy determined by this component at the given distance from it is small. For example, for this reason the admissible level of the magnetic component of the electromagnetic field is established in the sanitary rules only for frequencies of 60 to 1500 kilohertz.

In the required cases the estimation of the effectiveness of the shielding of the magnetic component is made analogously, but using the Biot-Savart formula which expresses the dependence of the effective value of magnetic field intensity on the current in the emitter, the distance to it and its geometric dimensions. This formula gives the simplest estimate and is valid for quasistatic fields. Its application turns out to be justified for the indicated frequency range and distances less than the emission wave length. On higher frequencies and at greater distances to the emitter the magnetic component is already negligibly small.

According to the Biot-Savart formula, the magnetic field intensity of a circular current (turn) nearby is

$$H=Ir^2_B/2(a^2+r^2_B)^{3/2}, \qquad (3.23')$$

where I is the effective value of the current strength; a is the distance from the center of the turna (along the axis) to the point at which the field intensity is determined; r_B is the turn radius.

The graphs of the functions $I=I(r_B)$ are presented in Fig 3.20 for various values of r_B/a:

$$I=\left(\frac{a}{r_B}\right)^3\left[1+\left(\frac{r_B}{a}\right)^2\right]^{3/2}2Hr_B, \qquad (3.24)$$

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where the values of H are recorded and are equal to the maximum admissible level of 5 amps/m. With these graphs it is possible to determine I, a and r_B satisfying the sanitary norms or the required shielding effectiveness. For example, for r_B=0.05 meters, a=0.3 meters and r_B/a=0.17 respectively, it is necessary that I≤110 amps. Otherwise it is necessary to increase a or change r_B. Let us assume that under these conditions it is necessary to have I≤260 amps. Then the shielding effectiveness of the turn must be no less than 2.4.

The indicated graphs can be used also for the inductive coil having n turns. Here it is expedient to propose that the magnetic field intensity increases proportionally to the number of turns, which is equivalent to an increase in the current by n times. Consequently, the shielding effectiveness must increase proportionally.

The shielding of the high-frequency devices can be provisionally divided into shielding of the generator itself and shielding of the process unit or the elements directly connected with the machined product, part, raw material or intermediate product. The shielding techniques and the shielding structure of the generator itself are the same as in the radio transmitters.

The shielding of process elements has its own peculiarities connected primarily with the variety of production processes using high-frequency currents.

Two basic types of process elements are distinguished: 1) induction coils in which the metals are heated and fused, 2) operating capacitors in which drying or welding of materials takes place using electric fields.

The planning and the design of the shields for the first type process elements are connected with defined difficulties caused by the energy losses in the shield, the necessity for insuring access to the melting furnace for mixing of the metal and the addition to it of some additional materials and also the creation of conditions to increase the output capacity, and so on.

Beginning with the required efficiency, according to the data in Tables 2.3, 2.4 and 2.5, the structural designs are selected for the basic elements of the shield. The shape of the shield must be simple: in the form of a circular cylinder or a rectangular parallelepiped with a square base. The shield dimensions are determined from preliminary calculation with respect to the admissible losses in the shield.

The radius R_{shield} of a closed shield of a fusion device or a device for hardening metals under the conditions that losses in it do not exceed 1% of the generator power, can be determined by the formula (2.2). If the induction coil of the process unit has a core which can be the fused or hardened metal, the shield radius decreases [23]:

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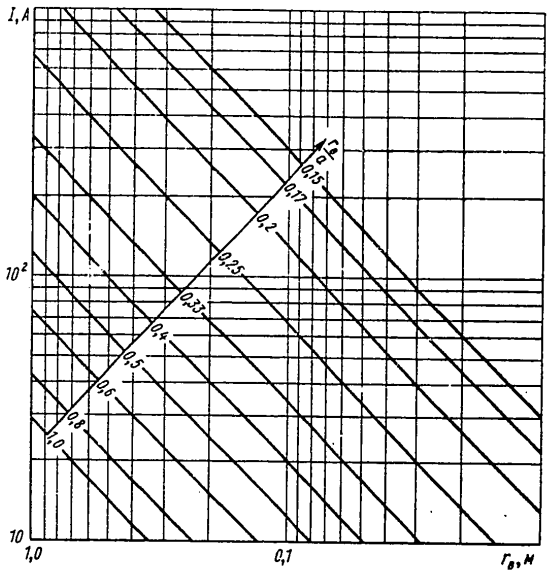

Figure 3.20. Nomogram for determining the parameters and the operating conditions of the coil (operating element) of a high-frequency device considering the biological shielding norms

$$R_{эк\,с}=0{,}75R_{эк}=6{,}4r_к\sqrt{\frac{I^2n^2}{\sigma\delta Pl_к/r_к}}. \qquad (3.24)$$

The shield height is determined by the formula [23]

$$h=l_к+2R_{эк}/3. \qquad (3.25)$$

If the dimensions of a steel shield are too large according to the calculations, then it is expedient to use aluminum.

For example, let it be necessary to determine the dimensions of steel and aluminum shields for the process element of the fusion furnace according to the following data: $r_к$=0.2 m, $l_к$=0.25 m, n=10 turns, I=450 amps, P=60 kilowatts, f=0.22 megahertz, $\sigma_{al}=3.8\cdot10^7$ (ohm-m)$^{-1}$, $\sigma_{st}=10^7$ (ohm-m)$^{-1}$. The problem is solved in the following order.

Depth of penetration with respect to (1.29):

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For steel

$$\delta_{ст} = 0{,}52\sqrt{\frac{\rho}{\mu_r f}} = 0{,}52\sqrt{\frac{10^{-7}}{150 \cdot 0{,}22}} = 0{,}3 \cdot 10^{-4}\ \text{м},$$

For aluminum

$$\delta_{ал} = 0{,}52\sqrt{\frac{\rho}{f}} = 0{,}52\sqrt{\frac{2{,}6 \cdot 10^{-8}}{0{,}22}} = 1{,}8 \cdot 10^{-4}\ \text{м}.$$

The radius of the cylindrical shield (2,2):

Made of steel

$$R_{\underset{(1)}{эк\ ст}} = 6{,}4 r_к \sqrt{\frac{I^2 n^2}{\sigma \delta P \frac{l_к}{r_к}}} =$$

$$= 6{,}4 \cdot 0{,}2\sqrt{\frac{10^2 (450)^2 \cdot 0{,}2}{10^7 \cdot 0{,}3 \cdot 10^{-4} \cdot 6 \cdot 10^4 \cdot 0{,}25}} = 1{,}15\ \text{м}.$$

Key: 1. steel shield

From aluminum

$$R_{\underset{(1)}{эк\ ал}} = 6{,}4 \cdot 0{,}2\sqrt{\frac{10^2 (450)^2 \cdot 0{,}2}{1{,}8 \cdot 10^{-4} \cdot 3{,}3 \cdot 10^7 \cdot 6 \cdot 10^4 \cdot 0{,}25}} = 0{,}25\ \text{м}.$$

Key: 1. aluminum shield

The height of the steel shield is

$$h_{\underset{(1)}{ст}} = l_к + \frac{2R_{эк}^{(2)}}{3} = 0{,}25 + 0{,}77 = 1{,}02\ \text{м},$$

Key: 1. steel; 2. shield

and the height of aluminum shield is

$$h_{\underset{(1)}{ал}} = 0{,}25 + 0{,}167 = 0{,}417\ \text{м}.$$

Key: 1. aluminum

In our example it is expedient to make the shield from aluminum.

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High-frequency energy is fed to the operating element by a coaxial cable with the corresponding matching of the wave impedances. In the powerful units in the absence of shielded feeders, metal buses are used instead of cable. These buses are fastened to the insulators and laid in metal boxes which are welded along the entire perimeter of the transverse cross section on one side to the generator shield and on the other side to the process element shield. In order to avoid significant losses in the feeder shield, its dimensions are selected correspondingly. The radius of the cylindrical shield as a feeder line, the thickness of the material of which is much greater than the penetration thickness, under the condition that the losses do not exceed 0.5% of the generator power for the entire feeder length L_f [23]:

$$r_{\text{э}\phi}^{(1)} = 8\sqrt[3]{\frac{I^2a^2L_\phi}{\sigma\delta P}}, \quad (2)$$

Key: 1. feeder shield; 2. feeder

where I is the effective value of the current in the feeder; a is the distance between the feeder lines; σ is the conductivity of the shield material; δ is the depth of penetration; P is the generator power.

In the same example when using aluminum and a=0.2 m, L_{feeder}=3 meters, the side dimension of a feeder with square crosssection is

$$b_\phi = 2r_{\text{э}\phi} = 16\sqrt[3]{\frac{I^2a^2L_\phi}{\sigma\delta P}} = 16\sqrt{\frac{(0{,}2\cdot 450)^2\cdot 3}{3{,}8\cdot 10^7\cdot 1{,}8\cdot 10^{-4}\cdot 6\cdot 10^4}} = 0{,}5 \text{ м}.$$

The shielding of the technological process element is realized considering the nature of the production process. For example, the hardening of small metal parts in the coil field can be accomplished in a wave guide filter which is open on the ends, just as the drying of bulk material in a capacitor field. Whereas in the first case the parts are fed by a belt which has translational motion, in the latter case with an inclined position of the capacitor the mass shifts under its own weight. Sheathing by a wave guide filter of the honeycomb type can be used as the shield for the operating press when welding plastic.

If the technological process takes place for a comparatively long time and no interference by service personnel is required, then the high-frequency device is placed in a shielded area (cab). Filtration of the network is required in this case.

The problems of the shielding of high-frequency industrial equipment have been investigated in more detail in reference [23].

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3.9. Shielded Facilities and Equipment Rooms

The shielded facilities, equipment rooms and cabs of mobile units are closed electromagnetic shields of comparatively large volume which can be used both for localization of the fields of their internal sources and for protection from the fields of the external emitters. In many cases the functions of this shield can have a mixed nature. They can be part of operating mobile or stationary radio engineering units, they can be used at industrial enterprises, in test areas and at medical institutions. The especially important role of these shields in the operation of measuring and testing complexes must be noted.

Simultaneously with the standardization of the radio-electronic equipment with respect to degree of development, series output and improvement, many of the shielded facilities, equipment rooms and cabs are becoming standardized, but the variety and number of conditions of their application lead to the fact that a significant part of the shields still remain unstandardized. The latter is primarily characteristic of unique units.

The recommendations presented below with respect to the construction of shielded facilities operating in a wide frequency band must be considered as an effort to generalize the existing ideas and the accumulated experience and present a detailed description of the developments that have been checked out in practice.

The structural designs are being developed in accordance with the technical assignment in which the requirements must be formulated reflecting the following:

The purpose of the facility, a brief characterization of the installation including it, the types of operations and regulations in the shielded facility;

Effectiveness of the shielding at given distances from the inside or outside wall in the emission frequency bands;

The expediency of using the radio-absorbing materials as a function of the nature and configuration of the field distribution inside the shield;

The general and special characteristics of the communications introduced into the shield, the mandatory diagrams of the cable connections, the electric power supply networks, the control, signalling and communications network;

Information about the work areas, the working conditions of the operators and their standard of living, lighting, heating, and so on;

The methods of placement, maintenance and transport of the equipment;

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The type of facility (stationary, collapsible, mobile);

The parameters of the admissible mechanical and climatic effects;

The procedure for location of the shielded facility with respect to the radio-electronic means within the boundaries of the facility or enterprise territory.

In addition, the requirements on safety engineering, the scientific organization of labor, engineering psychology and esthetics must also be taken into account.

The technical assignments stipulate the rules and the procedure to be followed in testing and accepting the shielded facility, chamber or cab, the procedure for the author's inspection during construction, installation and during operation and maintenance.

The facility and the machinery are considered to be shielded if their generating surfaces are sealed with respect to the electromagnetic field and insure limitation of the propagation of the electromagnetic energy both from the outside into the internal spaces of the corresponding closed shields and in the opposite direction, that is, from the shields.

The walls, floor, ceiling, window and door openings, ventilation system must be shielded in an electrically sealed facility, and the filters included in the corresponding networks. The parts are installed for attachment of the equipment.

The parts of the housing and the shell of the shield include the frame, the sheathing and the elements for attachment of the shield to the walls, the floor and the ceiling or the frame. The installation of large shielded facilities is made by attaching steel sheets directly to the surfaces of the facility. Before installation, the surfaces of the walls are plumbed. The sheets of the shield are welded to the floor in "patterns" (6 to 8 sheets each), they are covered on both sides with drying oil, red lead, Kuznetsk basin black or analogous materials, they are fastened to the walls and are welded to each other.

The "patterns" of the shield are attached to the walls using installation parts in the form of stays with a notch 16 to 20 mm in diameter and 150-200 mm long. Discs approximately 100x100 mm in size are welded to the stays in such a way that the ends of the stays will protrude 20 to 25 mm beyond the discs. Holes are cut in the "patterns" in accordance with the placement of the stays. The "patterns" are hung on the stays and are welded to them around the perimeter in a solid seam. The ends of the stays are cut off or used to hang the plaster lathing. Other methods of fastening the shield are possible, but in all cases warping of the shield sheets is observed to a greater or lesser degree. The straightening of the surfaces and decreasing their waviness are accomplished by the plaster coating.

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When the thickness of the leveling layer of plaster is no more than 50 mm, it is recommended that the plaster lathing be suspended on segments of reinforcing wire 3 to 4 mm in diameter and approximately 40 mm long welded to the shield. If the warping of the sheets is insignificant, the lathe can be fastened to the shield by spot welding.

In the case of significant curvature of the surfaces, the thickness of the leveling layer is more than 50 mm; vertical bars of reinforcing wire are installed plumb in the shielded space, to which the plaster lathe is fastened by binder wire. The lathing is then fastened by horizontal bars. The bars and the lathing are joined at the intersection points. The frame obtained in this way is welded to the shield at the joints or other points. The plaster is applied to the lathing. Melting parts must be provided in the shielded facilities by means of which the inside equipment is installed. These parts (stays, bolts) are mounted in the brick or concrete walls in the mortar, and they are welded to the shield in a solid seam at the points of intersection with it. Taking into account the fact that after welding the shield can be warped, it is necessary to use telescopic structural elements for the mounting parts.

It is recommended that the sheathing of the shields for small facilities be placed over the frame which insures smooth wall surfaces. In this case the walls are finished only by painting or covering with thick wallpaper. The structural design of the frame usually is arbitrary considering the placement and the thickness of the shield material. The frame is made of channel irons, angle iron and strip steel, and in the case of using thin material or lathing for the shield, the frame is made of wooden beams.

The shielding of the sealings is accomplished by laying the shield over the lower side of the ceiling tiles or on the floor of the next story up, which is possible when the shield is put down in a newly constructed building, and it is necessary that the ceiling has a complex configuration. The laying of the shield on the flor of the next story up is more complicated, for in order to maintain a seal it is necessary to install beams and ceiling tiles in welded "pockets." These "pockets" are welded around the entire perimeter to the walls of the shielded facility and the floor of the next story playing the role of a ceiling for the shield. The two methods can take different forms, but primary attention must be given to maintaining the electric seal.

The shielding of the floor has its peculiarities connected with the fact that the distortion of the shield leads to cracking of the floor and its overload layer. Therefore if the floor shield sheets are laid directly on the tiles over the cement coupler without any fastenings, then it is necessary to lay the overload layer 80 to 100 mm thick of the sheets, and to lay a wooden floor over the layer. The sheets of the floor shield must be welded overlapped 20 to 50 mm in a solid seam and welded to the wall shield. When the overload layer cannot be sufficiently thick, the floor shield is laid over a frame to which it is welded. If warping of the shield sheets is observed in this case, logs can be laid on it over which a decking is put down.

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Frequently the floor shield is fastened by anchor bolts to the tiles or stiffening ribs made of pieces of angle iron, channel iron, bar or reinforcing screen arelaid on the shield for this purpose. The reinforcing screen is made of bars 6 to 10 mm in diameter with a mesh size of 200x200 mm. The warping in the given case is decreased by spot welding of the shield to the bars.

It is not recommended that the floor shield be installed on packed ground; it can be laid on a concrete slab no less than 80 mm thick.

The installation of large shielded production facilities is complicated as a result of the necessity of shielding the channels, the beams, the cantilevers, columns and tiles. In order to maintain continuity of the shielding, the beams and tiles are laid in welded "pockets." These "pockets" must have special rims for welding to the shield and are usually made of the same material as the shield. These structural elements are investigated in detail in [38].

In order to insure access to the communication pipes introduced into the shielded facilities, frequently subfloor channels of the corresponding size and shape are built into the floor. If according to the process conditions these channels must be left open, they should be shielded. In other cases the floor under the channels is shielded by ordinary means using removable covers, around the perimeter of which contact systems are installed.

The parts of the door and window shielded openings are with respect to their structural design the most complex parts of the shield. The shield of the door or window opening is made up of a frame surrounding the opening and a door or window. The frame is welded to the wall shield around the entire perimeter of the door frame. The door is placed against the frame of the contact system. The frame for the door opening is made of angle irons of the corresponding size welded to the channel iron framing the opening. A copper or brass contact strip is fastened to the angle iron by wood screws and soldered. The door is made of steel 1.5 to 3 mm thick in a U-shape, and it is framed around the perimeter by a contact strip of phosphorous bronze 0.2 to 0.3 mm thick. One side of the strip is soldered, and the other is clamped under the metal strip along the entire perimeter of the door. The strip is screwed to the door. The contact plate has slits at the fastening objects, and therefore it can be shifted freely under the strip when the door is closed, squeezing porous rubber laid along the entire perimeter of the door under the contact. With the doors closed the rubber insures the required tightness of the contact and the contact of the door with the copper strip in the frame. In principle the shield of the shutter-type window can be made analogously. The shutters of the window can be open if necessary.

The described structural design has a number of deficiencies among which first of all it is necessary to consider the nonuniform contact along the entire perimeter of the opening and the absence of the possibility of regulating the contact pressure.

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Other designs of the shielded doors differing in size, shape, structure of the contact system and the number of doors are described in [38].

When it is necessary to insure high effectiveness of the shielding, double doors are used. The application of double doors with an entry chamber and additional blocking excluding the possibility of opening both doors simultaneously provides access to the shielded facility during operation without disturbing the operating conditions of the radio-electronic equipment. With this type of blocking one of the doors will still not be tightly closed, and the other will always be locked.

The entry chamber can be a separate attachment to the shielded facility or be part of it. In both cases the shield must be common for the facility and the entry chamber.

The shielding of a window opening, in addition to the required shielding effectiveness, must insure sufficient light, which can be achieved when using screen materials or wave guide structures. The use of glass with a conducting coating provides for sufficient light, but low effectiveness of the shielding in the frequency range of 300 to 1000 megahertz (about 30 decibels) limits their application. Most frequently the shielded facilities are installed without windows.

The shielding of the window opening with the application of a screen is made up of a stationary metal frame welded to the facility shield and a clamping (moving) frame between which the screen is placed with a mechanism for raising and lowering it. If a reliable contact is insured between the stationary frame and the screen along the entire perimeter, the shielding effectiveness reaches 60 decibels in the range up to 1000 megahertz. The window openings can be shielded by using shutters covered with screens, the installation of glass with current-conducting layer or a honeycomb type filter. The shutters are made of angle iron or sheet steel. A contact system with a common frame is installed around the entire perimeter of the shutter. It can be welded in a continuous weld to the shield of the facility.

The choice of the screen mesh size or the wave guide filters is made in accordance with the required shielding effectiveness. For example, in order to insure effectiveness to 80 decibels in the range to 10 megahertz with a shutter size of 1.0×0.5 m^2, the filter mesh size must be on the order of 0.1×0.1 m^2 and the length 0.2 meters.

The fittings for introducing communications include the structural elements required to restore electric and magnetic seal of the shield after running various channels through it, including the ventilation and life support system channels. The metal parts of this group must have continuous welded or soldered seams at the joints of the sheets, at the intersection points and at the points where the structural parts are fastened together. These

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parts must be welded to the shield and should not have flange connections. The channels made of nonmetallic materials (in particular, cement or brick in the engineering building facilities) must be replaced by metal pipelines or in order to increase the economy of structure these channels must be metal-plated at least at the points of their entry into the shield to the length required to insure the required effectiveness.

The introduction of various tubes and pipelines is always connected with the formation of holes which must be closed beyond the limits of the corresponding communications. The simplest solution is the use of a metal plate for this purpose through which the pipe is run. The plate is welded to the shield, and the pipe is welded to the plate around the entire perimeter of the transverse cross section. However, this procedure creates difficulties in replacing the pipe. It is recommended that the pipes be run into the shield through a piece of pipe of larger diameter and length equal to 4 or 5 diameters of this section. The section of large-diameter pipe is welded to the plate, and the plate to the shield in which the corresponding cut is made. After putting the pipe through the segment of larger diameter pipe, they are welded to it from either side. When replacing the pipe, an insignificant part of the connecting pipe is cut off at the location of the weld, and then the inside pipe requiring replacement is removed. The remaining open part of the entry does not interfere with the electric seal of the shield, for the entrance formed by the segment of large-diameter pipe has sufficient length. If a nonmetallic pipe is run through the entry, then the seal of the shield is not disturbed in this case either for the same reason. When laying cast iron pipe, the part of it for the length of the entry must be replaced with steel pipe which is welded. Then the cast iron pipes are connected on both ends to the steel pipe in mortar.

The segments of large-diameter pipe (entries) must be put in considering that the pipes running through them will form a rigid structural element having reliable contact with the general shielding. Therefore the pipes must be removed from each other a distance of no less than 40 to 50 mm, and they must be 150 to 200 mm from the floor and walls. The stands for the pipelines running near the corners of the facility must be placed 150 to 200 mm away from the two walls. It is also expedient to increase the rectilinear parts of the pipeline, for any type of bending complicates welding or mechanical connection of the pipe to insure contact with the entry to the shield.

The electric circuits are introduced, as a rule, through the interference-suppressing filter. The filters are installed on the outside of the shielded facility. The circuits from the filter to the shield must be laid in pipe, the ends of which are welded from one end to the facility shield, and on the other, to the filter housing. The circuits without filters are installed so that from the point of emergence from the shield to the housing of the instrument to which they are connected continuity of the shield will be insured. For this purpose it is necessary to create

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an electric contact of the shielding sheating of the cables with the facility shield at the point of entry of the network into the shield and with the housing of the instrument. All this is done using coaxial plugs. In the case where the effectiveness of the shielding of the cable braiding is insufficient, wire must be laid to the tubes. The structural design of the basic devices, the fastening of the shield and the inside finishing of the facility (machine room) are selected in accordance with the purpose by the data in Table 2.12.

3.10. Shielded Cabs

Stationary shielded cabs [38, 57, 58] essentially are shielded, small-size facilities. These cabs can occupy part of the facility and, as a rule, are mounted on a frame. The skin of the cab is made with the shielding material on the inside of the frame, and the outer surface of the cab can be finished in a decorative material.

The equipment area of a mobile unit, for example, an automobile, is sheathed in the shielding material on the outside of the frame; usually wood is used for the inside finish. The equipment rooms on ships are most conveniently shielded by using metal plating on the inside surfaces. The existing bulkheads are used as the base for the shield.

When it is necessary to create several work areas under production conditions excluding mutual effect of the instruments installed in them it is expedient to use the system of modules equipped on a common base (frame) and insulated from each other.

The stationary shielded cabs made of steel sheets insure high shielding effectiveness, but their installation is labor-consuming, and the cost is comparatively high. As is pointed out above, it is not always possible completely to realize the high effectiveness of the material itself. Therefore when the required effectiveness does not exceed 30 to 40 decibels, it is expedient to solve the problems of shielding by applying foil material, current-conducting paints, metal plating the surfaces, using screens, and so on. When manufacturing screens, the indicated materials are used only as the shells of the screens.

The screening of the openings in the cabs is done almost always with the application of metals, and the bearing mechanical base can be such materials as wood, plastic, textolite, building materials, and so on. This base must be rigid and correspondingly prepared in advance. The basic characteristics of the shielding materials are presented in Chapter 2. It is only necessary here to indicate the peculiarities of the installation of chambers.

As examples of the application of a current-conducting paint Fig 3.21, a shows the structure of the shielded door opening, and Fig 3.21, b, the installation in the chamber of a honeycomb lattice to provide for air

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exchange. The frame for the opening is made of wooden beams. Around the perimeter of the frame, a brass plate 4 is attached by wood screws. In the end of the door a bronze clamp is attached under which there is a sponge rubber pad 5.

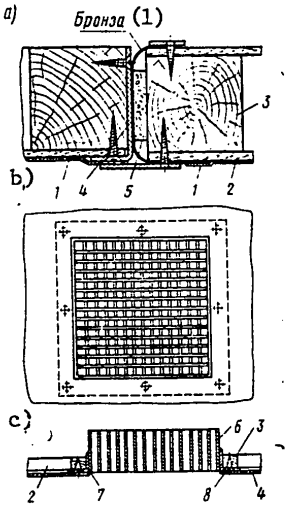

Figure 3.21. Sketch of the assemblies of the shielded chamber made using current-conducting paint

Key:
1. Bronze

The inside surface of the chamber is plywood (2). This surface is prepared in advance, that is, it is cleaned, spackled and dried. Then all of the metal surfaces are cleaned, and the spackling is finished. The paint 1 is applied using a paint sprayer in 5 or 6 coats, allowing each coat to dry. The installation of the "honeycomb lattice" is done with angle irons 7 which are fastened by wood screws 8 to the beams 3. The chamber is sealed to the metallized surface in an analogous manner. Foil materials are usually coated with a protective layer for which an oil-base paint or sufficiently heavy wallpaper can be used in all cases of the application of thin materials.

The collapsible shielded chambers (cabs) distinguished by structural simplicity, lightness, convenience and speed of assembly and dismantling have become widespread. Primarily these include the chambers inwhich the shielding material is a metal screen which insures sufficient shielding effectiveness and the required air exchange without the application of ventilation units. The shielding effectiveness of a chamber made of copper screen with a mesh size of 1.26x1.26 mm and a wire diameter of 0.3 mm at a frequency of 0.1 megahertz is greater than 100 decibels, and at a

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frequency of 100 megahertz it is 40 decibels. If it is necessary to obtain great effectiveness, the chambers are used with a double screen which increase the shielding effectiveness reckoned in decibels by 1.5 to 1.7 times by comparison with the chamber made from a single screen.

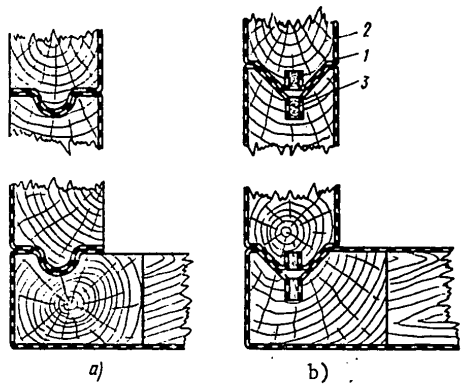

Figure 3.22. Panels of screened chambers with ordinary (a) and double (b) screen

The chambers are assembled from individual panels. For example, a complete chamber with a usable area of 9 square meters includes 22 panels, and for a chamber of 3 square meters, 12 panels are used.

The chamber panels are a wooden frame 2 with a single or double screen 1 stretched over it (see Fig 3.22) which is fastened at intervals of no more than 100 to 150 mm. In order that the chambers with the double screen provide increased shielding effectiveness, it is necessary that each screen be an independent closed shell. Therefore electrical contact between the shells of the inside and outside shields will not take place in the cab. For this purpose, a longitudinal groove is made in the recess and on the crest of the panel where the edges of the outside and inside screens are laid, and between the screens an insulating (usually wood) block 3 is inserted in the groove which does not permit the screens to become misaligned and make contact with each other. Considering, however, the necessity for grounding the shield, connection of the screens at one point is permitted. This is done on the housing of one of the filters located at the entrance of the networks to the chamber. An example panel size is 900x2500 mm.

In one of the chamber panels a single door is installed (see Fig 3.23). The door 4 has a screen 1 stretched over it, and it is framed around the perimeter with a bronze contact strip 2 under which porous rubber 3 is laid. For the chamber with double screen, the contact strip is split into two parts insulated from each other just like the screens.

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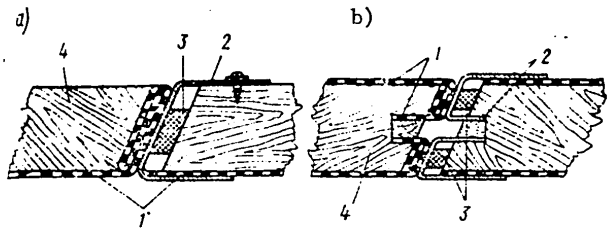

Figure 3.23. Shielding for a door opening using a single (a) and double (b) screen

Since in the collapsible cabins the application of solder when joining the panels is excluded, their mechanical contact must be such as to insure reliable contact between the parts of the screen shells.

Two types of joints of the panels are distinguished: angular (mutually perpendicular panels) and rectilinear (joined panels form a single plane). In both cases a tongue-and-groove joint is recommended (see Fig 3.22) and fastening the panels using split loops or angle irons and bolts. The angular joining is recommended by special spiral tension locks (see Fig 3.24) installed inside the shield. These locks are very convenient to maintain, and they insure reliable joining of the panels and facilitate the assembly and dismantling of the cab.

Figure 3.24. General view of a spiral tension lock

The deficiencies characteristic of the chambers made of electrically thin materials, for example, a screen are in practice eliminated in chambers made of steel sheets. For example, a collapsible chamber made of steel sheets contains 12 like panels (see Fig 3.25), and the total area of the chamber is 4 m^2. The frame of the panel is made of a steel equal-sided angle iron (30x30x3). It is covered with sheet steel 1 to 1.5 mm thick. One of the panels is made with a door which has a contact system of the spring-loaded comb type, and the other has a ventilation opening shielded by a honeycomb lattice. The house is assembled using bolts. The angular joint is made using a special angle iron illustrated in Fig 3.26. The sealing of all of the connection points is achieved by using brass mounting brackets.

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The effectiveness of the shielded facilities and chambers is calculated by the formulas presented in Chapter 2. It is possible to estimate the effectiveness by using the data in Table 2.12. The actually obtained shielding effectiveness is established by control measurements of the fields inside and outside the shields which are taken with the fully completed facilities (chambers) after installation of all of the equipment designed for the operation in them and connection of filters to the cable entrances.

The shielded facilities are widely used when performing special measurements. If these measurements, just as the measurements of the shielding effectiveness, are performed by a procedure which has not been worked out for the given specific conditions without considering all of the basic factors creating and masking errors in the absence of normalized indexes for the facility (cab), the results can be highly unreliable. In particular, in order that the results of the measurements of the electromagnetic fields in shielded facilities (cabs) from sources located in them, which are very important for evaluating radio-electronic equipment and shields, not differ from the results of the measurements taken in "free" space, it is necessary to preserve the primary structure of the direct emission field and attenuate the diffuse field intensity to the maximum which arises as a result of multiple reflections of electromagnetic waves from the inside surfaces of the closed shield.

Several satisfactory solutions to this problem are known.

The first of them consists in the fact that the measurements are performed in direct proximity to the transmitter antenna where the direct radiation field is predominant. By the direct proximity we mean the range of values of the distance from the emitter to the reception point corresponding to the inequality $2\pi r/\lambda \ll 1$. Then the dimensions and the parameters of the transmitting and receiving antennas and the distance of the reception point can be selected so that in the measurement zone the field will be uniform. This is possible if the distance from the emitter to the surrounding objects is approximately an order higher than its linear dimensions, and the maximum of these dimensions L_m satisfies the inequality $L_m/\lambda \leq 0.25$ [59].

The second procedure consists in the fact that the measurements are performed on frequencies significantly below the minimum resonance frequency of the shield where the field distribution in it in practice does not depend on the frequency.

This offers the possibility of characterizing the shielded facility by the experimental data permitting a decrease in the measurement error [59].

The third possibility consists in assignment of a special shape to the inside surface of the shield permitting the reflected electromagnetic waves to hit part of the volume of the shielded facility in which the receiving

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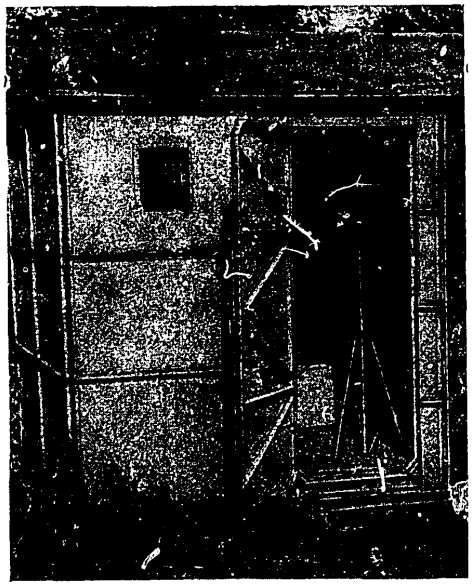

Figure 3.25. General view of a collapsible enclosure or dog house made of steel sheets.

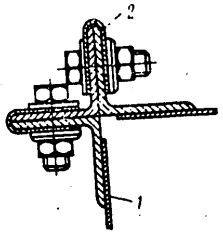

Figure 3.26. Angular connection of the panels of a collapsible chamber made of steel sheets:
1 -- shield; 2 -- mounting clamp

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antenna is located only after multiple reflections from the shield surfaces. For example, in the shielded facility the linear dimensions of which are commensurate with the operating wave length, when using the aperture diaphragms made of screen materials it is possible to obtain a volume in which the diffuse field will be sharply attenuated. Then the error can be reduced to the admissible limits by introducing the corresponding correction.

Finally, one of the improved and widespread methods of measuring electromagnetic fields in the frequency band above 80 megahertz is the application of echoless chambers [29, 60, 61].

By the echoless chamber usually we mean a closed electromagnetic shield, the inside surfaces of which have ordinary or special shape and are completely or partially covered with radio-absorbing materials. The inside echoless chamber can be divided into two parts (zones); part of the chamber in which the spurious fields called the echoless zone are attenuated to the maximum (the quiet zone, the operating zone), inside which the measurements are taken: the other part of the chamber is the emission zone where the transmitters are located.

In a rectangular chamber with flat surfaces coated with radio-absorbing material, the diffuse field level in the echo-free zone is determined by the quality of the radio-absorbing material. The expedient selection of the profile of the inside surface of the echoless chamber can insure additional attenuation of the beams reflected from the surface in the echoless zone by 20-30 decibels if the beams incident in the echo-free zone have undergone double or triple reflection before this.

The development of the echoless chamber is a complex engineering problem including the calculation of the radio technical part, the inside surface profile, consideration of the nature and accuracy of the performed measurements, the development of the structural design of the basic assemblies and chamber as a whole, the determination of the overall dimensions, the installation process, the selection of the materials and a number of other problems.

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